FINAL PROJECT

Mechanical Engineering

MANUFACTURING PARAMETERS CHARACTERISATION OF A 3D PRINTER

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0.2. Abreviattion list

FFF: Fused Filament Fabrication

AM: Additive Manufacturing Technologies

ANOVA: Analysis of Variance

CAD: Computer-Aided Design

DTM: Desktop Manufacturing

FDM: Fused Deposition Modelling

CNC: Computer Numerical Control

ABS: Acrylonitrile Butadiene Styrene

GPU: General Public Licence

DOE: Design of Experiments

LCD: Liquid Crystal Display

Etot: Total Error

Eres: Resolution Error

Eacc: Accidental Error

h: thickness

A: area

S: Standard Deviation

N: number of measurements

σ: traction resistance

e: deformation

L: length of the sample

L0: initial length

E: Young Module

σ: Yield Strength

σy: 0.2% Offset Yield Strength

σmax: Ultimate Tensile Strength

emax: Maximum deformation

MR: Resilience Module

MT: Tenacity Module

η: signal relations-noise

SN: Signal-Noise

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0.4. Abstract

The present project is based on the need of a deeper knowledge on the possibilities that the Fused Filament Fabrication (FFF) technique can offer, this is probably one of the most prominent manufacturing techniques inside the Additive Manufacturing field (AM).

3D printing has entered strong inside the user market in the recent years for the opportunity it gives day to day and casual users to manufacture their own parts and work on their own projects. But this technology has been around for some years now inside the mechanical industry as a source to create more customizable and unique parts.

Additive manufacturing has started to settle and stablish itself as a method to create final and usable parts for final products but has yet to exploit all of its potential in this field due to the fact that it is still not know all of the upsides and downsides that the technique can provide. This comes from the fact that there is an incredible amount of parameters that can affect the mechanical properties and the final appearance of the parts.

This being said, this project focuses on the study of the effect that the following parameters have on the mechanical properties of the manufactured pieces while submitted to a traction force in order to know the behaviour that the final part:

-Nozzle diameter

-Layer height

-Fill density

-Speed

-Orientation

In order to do this an experiment design (DOE) based on Taguchi's statistical method was carried out. This allowed to study each factor individually as well as the relation the three most important factors (Nozzle diameter, Layer height and Fill density) have with one another. After all the results were obtained we used a variance analysis to corroborate which of the manufacturing parameters had more influence in each of the mechanical properties studied.

The mechanical properties studied in this project are the following:

- Young Module

-0.2% Offset Yield Strength

-Ultimate Tensile Strength

-Maximum Elongation

-Resilience Module

-Tenacity Module

The material used to create all the test's specimens was Acrylonitrile butadiene styrene (ABS).

El present projecte es basa en la necessitat d'obtenir un major coneixement en les possibilitats que la tècnica Fused Filamen Fabrication (FFF) pot oferir, aquest sistema de fabricació es probablement la tècnica més prominent dins el camp de Additive Manufacturing (AM).

La impressió en 3D ha entrar fortament dins el mercat d'usuari en els últims anys degut a les oportunitats que ofereix al consumidor de carrer de fabricar les seves pròpies peces i treballar en els seus propis projectes. Aquesta tecnologia porta ja uns anys dins de la industria mecànica com a recurs per crear peces úniques i totalment personalitzables.

La fabricació per adició ha començat a establir-se com un mètode per crear peces finals i que es puguin fer servir per a productes reals, però encara ha d'acabar d'explotar tot el seu potencial en aquest camp degut a que encara no es coneixen tots els punts positius i negatius que aquesta tècnica pot proporcionar. Això es degut a que existeixen moltíssims factors que poden afectar a les propietats mecàniques i l'aparença d'una peça durant la fabricació.

Aquest projecte s'enfoca a estudiar l'efecte que els següents paràmetres tenen sobre les propietats mecàniques d'una peça sotmesa a forces de tracció amb l'objectiu de ser capaços de predir el comportament de peces finals. Els paràmetres de fabricació són:

-Nozzle diameter

-Layer height

-Fill density

-Speed

-Orientation

Per aconseguir-ho, s'ha dissenyat un experiment (DOE) basat en el mètode estadístic de Taguchi. Això ha permès estudiar individualment cada paràmetre i la relació que tenen els tres paràmetres mes importants entre ells (Nozzle diameter, Layer height i Fill density). Desprès de l'obtenció dels resultats s'ha utilitzat un anàlisis de variància per corroborar quin dels parametres té mes influencia en les propietats mecàniques estudiades.

Les propietats mecàniques estudiades en aquest projecte són:

- Young Module

-0.2% Offset Yield Strength

-Ultimate Tensile Strength

-Maximum Elongation

-Resilience Module

-Tenacity Module

El material utilitzat per les provetes per als tests ha estat Acrylonitrile butadiene styrene (ABS).

El presente proyecto se basa en la necesidad de obtener un mayor conocimiento en las posibilidades que la técnica Fused filamento Fabrication (FFF) puede ofrecer, este sistema de fabricación es probablemente la técnica más prominente dentro del campo de Additive Manufacturing (AM).

La impresión en 3D ha entrado fuertemente en el mercado de usuario en los últimos años debido a las oportunidades que ofrece al consumidor de calle de fabricar sus propias piezas y trabajar en sus propios proyectos. Esta tecnología lleva ya unos años dentro de la industria mecánica como recurso para crear piezas únicas y totalmente personalizables.

La fabricación por adición ha empezado a establecerse como un método para crear piezas finales y que se puedan utilizar para productos reales, pero aún debe terminar de explotar todo su potencial en este campo debido a que todavía no se conocen todos los puntos positivos y negativos que esta técnica puede proporcionar. Esto es debido a que existen muchísimos factores que pueden afectar a las propiedades mecánicas y la apariencia de una pieza durante la fabricación.

Este proyecto se enfoca en estudiar el efecto que los siguientes parámetros tienen sobre las propiedades mecánicas de una pieza sometida a fuerzas de tracción con el objetivo de ser capaces de predecir el comportamiento de piezas finales. Los parámetros de fabricación son:

-Nozzle diameter

-Layer height

-Hijo density

-Speed

-Orientation

Para ello, se ha diseñado un experimento (DOE) basado en el método estadístico de Taguchi. Esto ha permitido estudiar individualmente cada parámetro y la relación que tienen los tres parámetros más importantes entre ellos (Nozzle diameter, Layer height e Hijo density). Después de la obtención de los resultados se ha utilizado un análisis de varianza para corroborar cuál de los parámetros tiene más influencia en las propiedades mecánicas estudiadas.

Las propiedades mecánicas estudiadas en este proyecto son:

- Young Module

-0.2% Offset Yield Strength

-Ultimate Tensile Strength

-Maximum Elongation

-Resilience Module

-Tenacity Module

El material utilizado para las probetas para los test ha sido Acrylonitrile butadiene Styrene (ABS).

1. Introduction

In the chapter it is explained which is the motivation to develop this project as well as the objectives that want to be achieved when the study is finished.

1.1. Motivation

Additive manufacturing has created lot of interest and investment in grand variety of fields of work and study due to the great potential it holds and the revolutionary technique it uses. The basic concept of this manufacturing method is to create a physical 3D part created from the initial design by a computer (CAD), and then printed layer by layer in the necessary order to end un achieving the desired shape and structure.

The versatility in design, flexibility and rapid prototyping which allows for continuous improvements in design, reduced production costs due to the fact that there are not intermediate tools or processes to generate the final part, customization and exclusivity of design, creation of complicated geometries that would be impossible or really expensive to produce with other processes, a lower environmental impact since the manufacturing produces almost no waste making production more environmentally friendly, etc. These characteristics are some of the advantages and possibilities that this manufacturing technique offers.

Even though additive manufacturing (AM) offers all these positive characteristics it still has to surpass all the technical challenges that have to be met in order to become a perfectly stablished manufacturing technique.

One of the main problems additive manufacturing faces is related to the quality of the final part. This happens due to the fact that there is a big amount of technical parameters that can be modified in order to change the appearance or the structure of the final part, but we have still to truly know how they really affect the product. The only way we have to do that by now is through trial and error but for this technique to be well stablished that shouldn't be the way to test the parts.

Because of this, the project has focused on the study of the mechanical behaviour of manufactured parts though FDM and submitted to traction tests with the objective of finding a way to characterize the influence that the manufacturing parameters have over the mechanical behaviour of final parts.

1.2. Goals of the study

The main goal of this project is to find out the most efficient way of manufacturing final products that will be used in specific working situations with the knowledge that we will have obtained through the experimentation of specimens manufactured via FFF that will be submitted to traction forces. These specimens will be fabricated with the additive manufacturing 3D printer BCN3D which uses FFF technology. The material used to manufacture the specimens will be Acrylonitrile butadiene styrene (ABS). This project intends to carry out the following points:

- Stating the state in which 3D printing is right now. This includes going through the projects that have studied the mechanical properties of samples created through FFF.

- Select those parameters that after having exhaustively analysed all the data available to us, we think are the more relevant or influential in order to create parts that have to be submitted to traction forces.

- Using Taguchi's orthogonal arrangement develop an experimental design involving the previously selected parameters.

- Designing and manufacturing the specimens necessary to carry out all the traction tests according to the specifications stated in the procedure.

- Select those manufacturing parameters that are more influential when determining the mechanical behaviour of the final part under traction forces. This selection will be done analysing the results obtained.

- Reach conclusions on the optimal values of the different parameters used during the manufacturing of the parts to obtain the best mechanical characteristics.

2. Basics of the Fused Filament Fabrication (FFF) and 3D printing

Being the 3D printer an irreplaceable tool to be able to complete the project it is important to understand how the machine works and which are the basic parameters that can have an effect on the final product or during the fabrication.

The manufacturing process works by pushing a thermoplastic filament with the use of some rollers or any other system to a resistance that melts the material (Figure 3.1). Afterwards it is deposited in a hot bed layer by layer. After a layer is sitting on the hot bed, it will solidify and another layer will lay on top of the previous one. By repeating this process, a full structure and finally a final product is obtained. The most common used materials are ABS and PLA although each day lots of new materials come out, mostly with the objective to better the looks of the final part (oxidation and wooden look, different kinds of colors, fluorescent materials...).

The work after the printing is also as important as the printing itself. In many occasions the part or object printed will have little imperfections that can be corrected (pointy edges, little holes...). These imperfections can be treated with sandpaper or acetone.

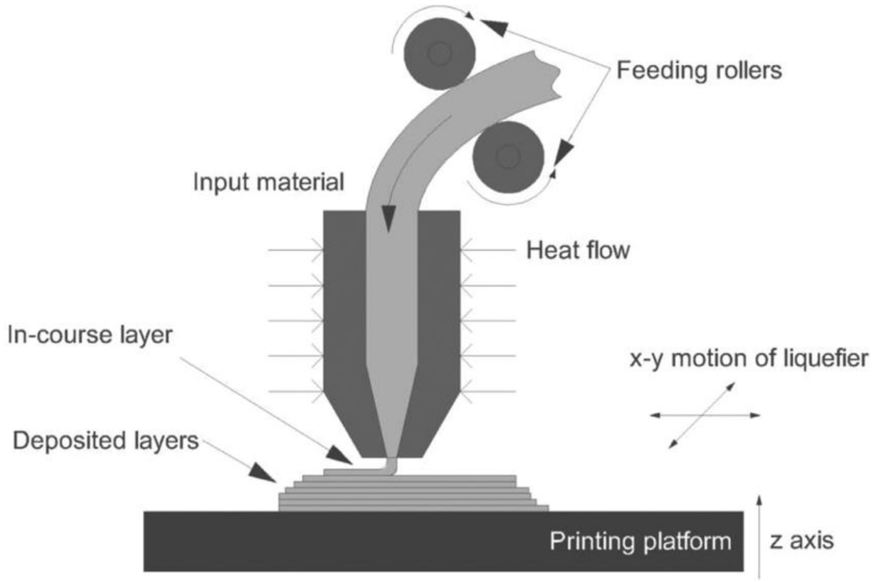

Figure 2.1: Travieso-Rodriguez, J.A. (2016). Finite element analysis of the thermal behaviour of a RepRap 3D printer liquefier [Figure]. Recovered from https://www.researchgate.net

It is important to keep in mind that this description embraces the basic principle of FFF 3D printing but that there are many different and complex ways to achieve the same or better results.

2.1. Basic manufacturing parameters

It is as important to understand the physical part of the machine as the little elements that will make the manufacturing different. This section will explain the basic manufacturing parameters of a 3D printer. This will be done by going through the Slic3r software used during the project. This will be useful in order to make sense of the parameters used and the software utilized at the same time.

2.1.1. Layers and perimeters

These are the manufacturing parameters in charge of the size and properties of each of the layers that will be printed.

- Layer height: controls de height of the layers printed and thus how many layers will be necessary in order to finish the part.
- First layer height: it allows changing the value of the first layer printed independently of the rest. This may be an interesting option when working with really low layer heights in order to make sure that the first layer sticks correctly to the plate or hot bed.
- Perimeters: when printing a layer, the first thing that the software does is printing the contour lines that delimit the layer. This option gives the option to repeat the contours as many times as wanted before printing the interior part of the layer.
- Solid layers: when printing objects that are not completely filled inside it is important that the outer layers are 100% full. This option lets us choose how many layers we want in the top and in the bottom of the parts.

The software also gives the option to act “intelligently” when printing. If wanted to, it will print more perimeters than the ones set if it thinks that they are needed, moreover, if two walls don’t match it will make sure to put them together if wanted (Figure 3.2).

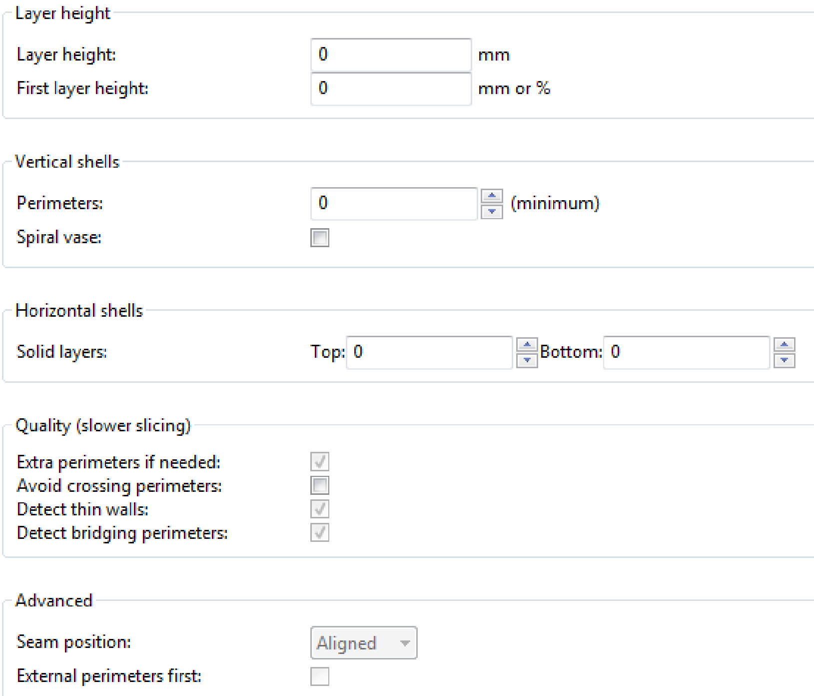

Figure 2.2: Layer and perimeters options

2.1.2. Infill

These are the manufacturing parameters that have an influence over the interior part of the printed object. Its sizes, structures and quantities (Figure 3.5).

- Fill density: it is the option to choose how many % of material goes inside the printed object (Figure 3.3). If it's an object just for show this option will be set in a low value but if the part printed needs to be under some kind of stress forces it might be better to set higher values.

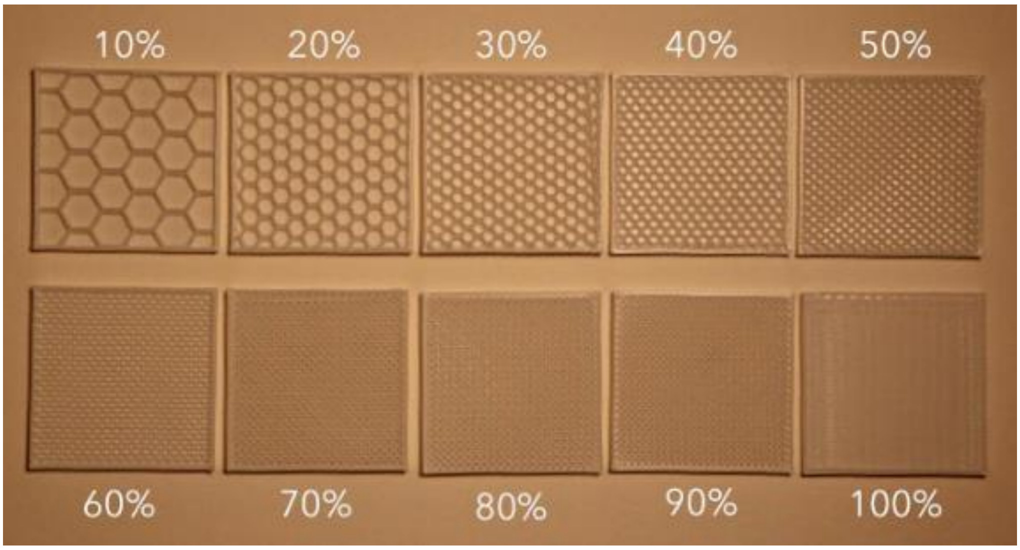

Figure 2.3: García Romero, Maria. (2016). Visual representation of the % of fill density (Figure). Recovered from https://impresoras3d.com

- Fill pattern (figure 3.4): this will decide the shape of the interior layers and threads from the object. Rectilinear, line, concentric, honeycomb, Hilbert curve, Archimedes chords are some of the options the Slic3r software offers.

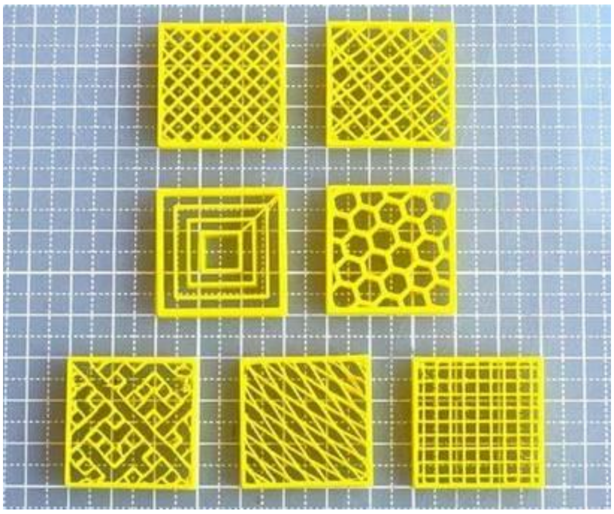

Figure 2.4: Some of the existing fill patterns

- Combine infill every: this feature allows combining infill and speed up the printing by combine infill layers while preventing thin perimeters, thus accuracy.
- Only infill where needed: this option will prevent areas printed only with support purposes to be filled by material.
- Solid infill every: this feature allows to create a solid layer every X layers to make the structural integrity of the part better.
- Fill angle: this option chooses the angle of the infill printing.
- Solid infill threshold area: this feature creates a solid infill if the software feels like the structure will benefit in small areas.

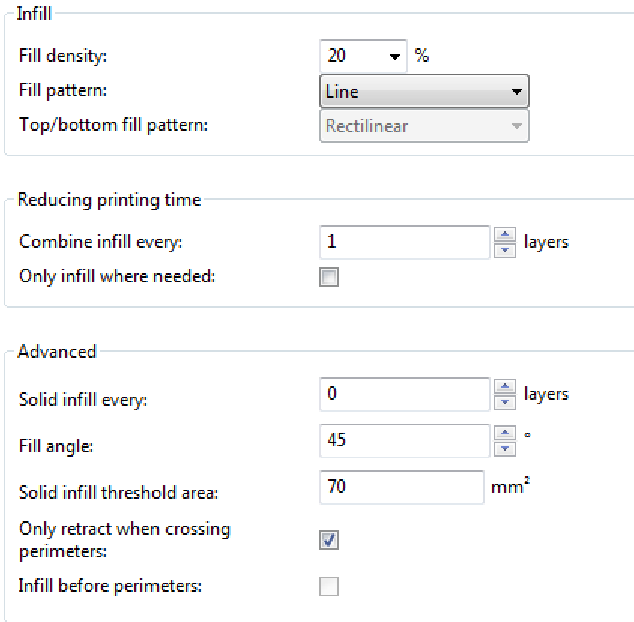

Figure 2.5: Infill configuration options

2.1.3. Skirt and brim

These sets of options (Figure 3.6) don't affect directly the quality or the configuration of the printed part. In some printers, when taking out the previous printed object it is necessary that the distance between the nozzle and the hot bed is the exact. These options allow to create a set of perimeters independent from the ones of the object in order to have time to calibrate the printer before the actual printing of the part.

It can be chosen how many perimeters we want to print and the distance to the actual object. These perimeters can also have layers to ensure that the first layers (the most important ones) will be perfect (Figure 2.6)

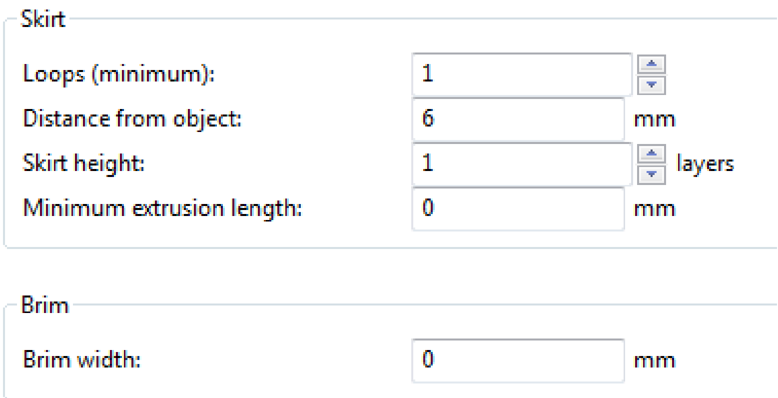

Figure 2.6: Skirt and brim configuration options

2.1.4. Support material

The support material is one of the most useful options of the 3D printing softwares. This support material allows printing layers in the air where there wasn't a layer before. The printer prints a support-like structure which sole objective is to allow the machine to print on top of it (Figure 3.7). The support material will have to be removed after the printing of the object. This support material is most useful when the 3D printed have to printing heads, one can contain the object material and the second one the support material which will be easier to remove. If the support material is made out of the same material as the main object we might encounter some problems when trying to remove it. It is always advisable to use tools so when it is remove it the main part looks good.

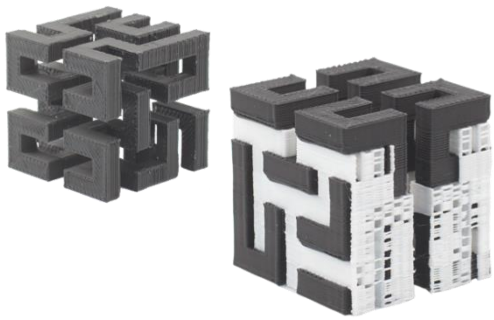

Figure 2.7: 3Dfabprint. (2016). Main material in grey and support material in white (Figure). Recovered from www.3Dfabprint.com

It is important to highlight the Raft layers' options, which allow us to generate support material under the actual object to print over it (Figure 3.8).

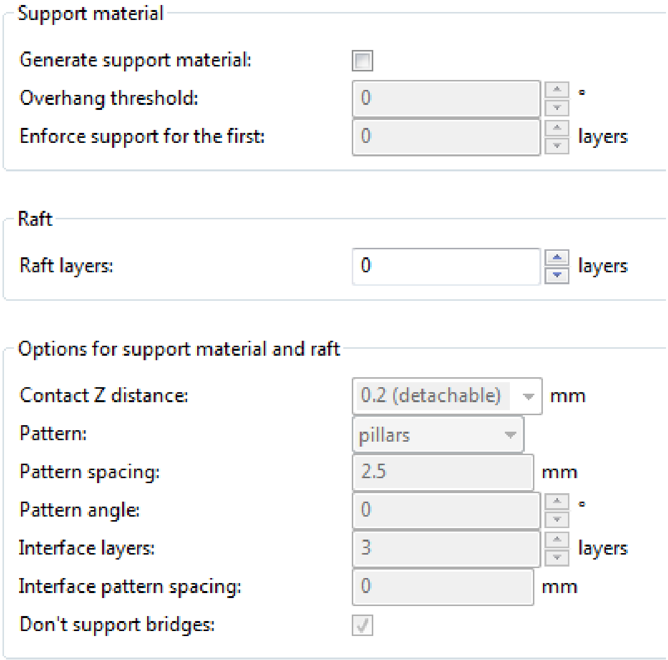

Figure 2.8: Support material configuration options

2.1.5. Speed

This set of parameters change the different speeds that take part during the manufacturing of the object. There are lots of speed values that can be changed but the most important ones are the following (Figure 3.9):

- Perimeters: modifies the speed of the perimeters.
- Infill: modifies the speed used to print the infill of the object.
- Support material: modifies the speed used to print the support material of object.
- Gap fill: modifies the speed of the machine when trying to automatically fill small holes or gaps in the printed part.

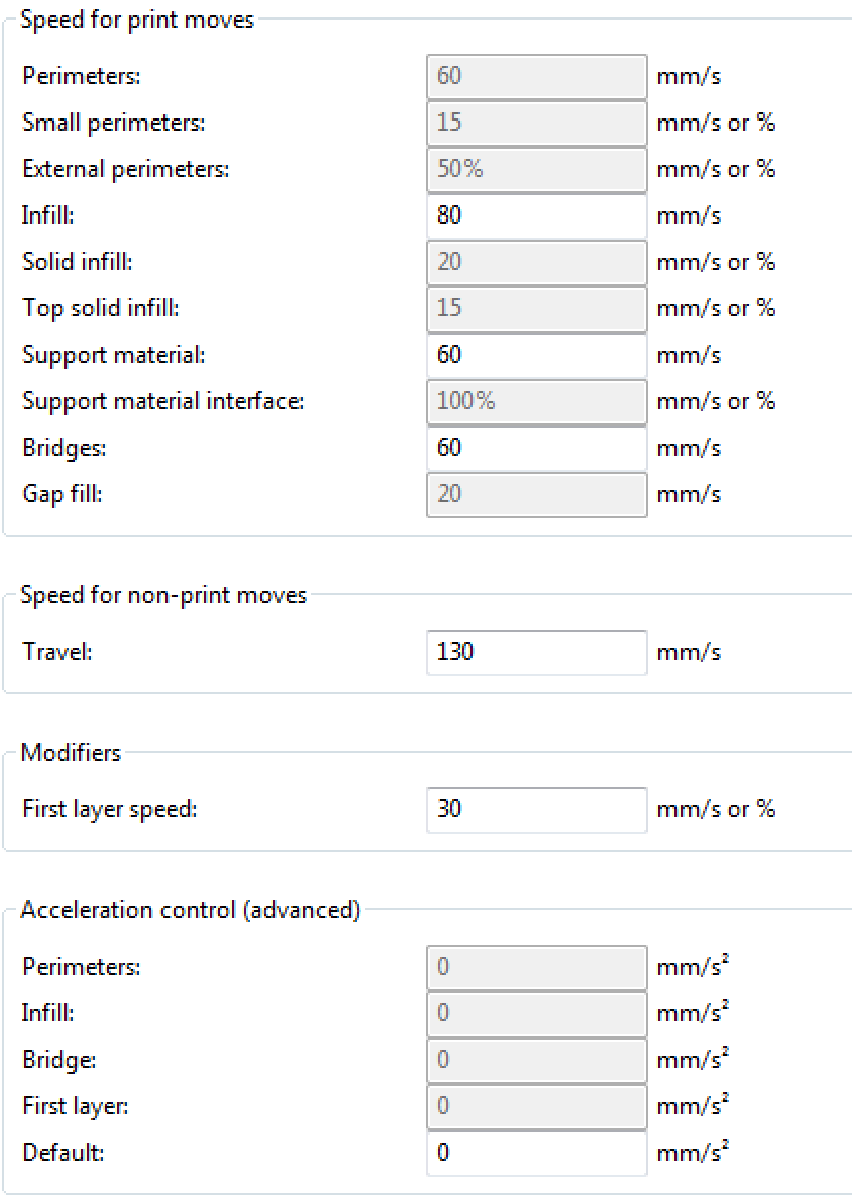

Figure 2.9: All the speed configuration options for Slic3r

2.1.6. Orientation

The last parameter that is important to mention is the orientation. This manufacturing parameter doesn’t play a vital role in objects that are just printed for show but it is of great import when it comes to printed part that are going to be under stress forces. It will be stated later on that orientation is a fundamental property in the case of the parts that are designed to be used and sustain efforts.

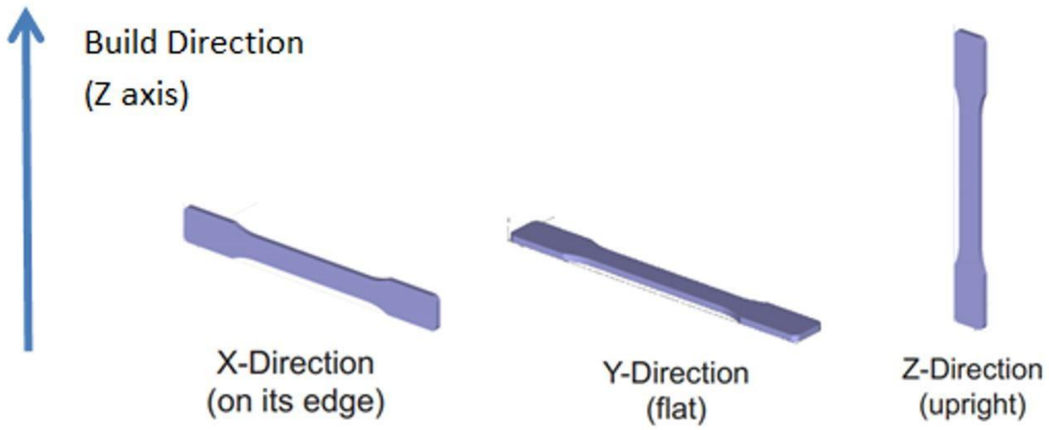

Figure 2.10: Matthias Fischer, M. Sc. (2014). Different sets of printing orientations (Figure). Recovered from https://www.sculpteo.com

Apart from the three main directions shown in the 3.10 figure, it is also possible to rotate the object based on any of the X, Y or Z axis.

2.2. Structural integrity of the 3D printed parts

Apart from the fact that there are parameters that can make better a 3D printed part's overall structure, it is not necessary to go blind into the tests without knowing what are we going to obtain. There a few physical properties or basic knowledge that can help better the understanding of a 3D printed object.

The creation of the layers occurs through the deposition of filaments that adder to each other horizontally when they are part of the same layer and vertically when they stick to the layers above or beyond them (Figure 3.11).

Figure 2.11: Matthias Fischer, M. Sc. (2014). Thread's deposition and union (Figure). Recovered from https://www.sculpteo.com

This process happens when the polymeric chains of the deposited filament unite with the ones from the previous extruded thread. This union create the bind in charge of keeping them together and capable of sustaining some amount of effort.

Another factor to take into account are the directions that the forces that will affect the part will have. If the force applied is a compressive force, the threads should be parallel to the direction of the force in order to be able to sustain a higher stress load. On the other hand, if the part is under traction forces, the threads should be always placed in the same direction of the force.

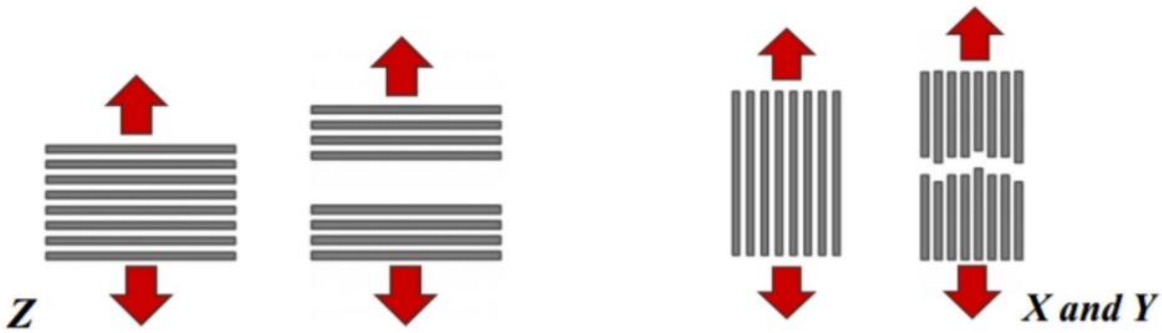

Figure 2.12: Matthias Fischer, M. Sc. (2014). Effect of the traction forces (Figure). Recovered from https://www.sculpteo.com

On the Figure 3.12 the left structure would be much more susceptible to breaking with much more little force than the structure that the right part has.

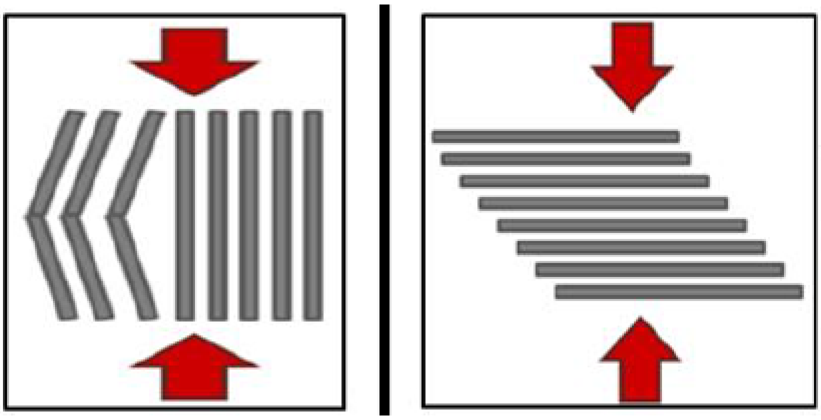

Figure 2.13: Matthias Fischer, M. Sc. (2014). Effect of the compression forces (Figure). Recovered from https://www.sculpteo.com

On the Figure 3.13 the left structure would also resist a much less amount of stress than the structural configuration that the part on the right has.

This being said, the size of the extruded threads also has an impact on how solid or resistance a 3D printed part is. The union between thicker threads makes for a better molecular diffusion, because they can gather more thermal energy which creates better unions. The thread's size is affected by the expansion of the material when coming out of the nozzle, this phenomenon is known with the name of swelling. This happens because the flux of polymeric material is forced throw the nozzle to manufacture the part with the adequate geometry. This phenomenon is related to the elasticity of the polymer because of the possibility that the molecular system has to contract and expand itself: when the thread is in a liquid state and goes through the nozzle, the material suffers a contraction that later partially disappears when it exits the nozzle and the restriction effects disappear. Even if this effect happens, because it is known beforehand, the software that divides the part in layers corrects it, because the diameter of the extruded filament can be controlled through the extrusion head translation velocity and the plastic flux

3. Experiment

Once we have seen the parameters that take place in the fabrication process and how they intervene or what they do to the mechanical behaviour of the parts created via FFF it is intended to create a valid experimental method to determine which are the manufacturing parameters that have a bigger influence at making the final parts made of ABS more resistant to traction forces.

The ABS specimens used in this project have been manufactures using the BCN3D+ 3D printer. The parameters which are going to be studied are the following:

- Nozzle Diameter.
- Layer Height.
- Fill Density.
- Speed of the Nozzle.
- Orientation.

This will be done through the traction tests of the specimens. The results of these tests will allow us to know which are the parameters that have a heavier influence in the fabrication of parts that are going to be under traction forces.

The traction test will consist on submitting the specimens to traction forces and measure the lengthening of them due to the force applied so it is possible to determine the effort-deformation of the material used (ABS), then make the traction graph and be able to calculate the following parameters:

- Unitary Effort.
- Unitary Lengthening.
- Young's Module.
- Elastic Limit.
- Maximum Effort.
- Maximum Lengthening.
- Resilience Module.
- Tenacity Module.

To obtain reliable results with the minimum number of tests the experiment has been designed using a Statistical Design of Experiments (DOE), and the Taguchi method has been chosen due to the sturdiness it offers. Finally, a variance analysis (ANOVA) has been used to detect the most significant parameters and the level of influence to traction of the specimens when they are under this kind of forces.

Every step along the followed process is explained in this section.

3.1. Parameters and Experiment Design

The parameters chosen, the experiment and specimen design, the 3D printer, the data acquisition software's and the maths behind the data calculation are all explained in this section.

3.1.1. Manufacturing parameters studied

The selection of parameters has been done after having studied and investigated all the data available. These investigations where focused in the mechanic properties of the parts manufactured using additive manufacturing, and also other aspects, like the superficial result and the cost. It is worth mentioning that these investigations have also helped in the previous sections of the project to comprehend the functionality and the behaviour of the different manufacturing parameters. This way it has been possible to determine which parameters where more interesting and relevant for the study.

The parameters selected for the study are the following:

- **Nozzle diameter:** the filament's thickness has been modified by changing the size of the nozzle by which it is going through.

- **Layer height:** It's the thickness of each layer and it will determine how many layers are needed to create the part. There are several factors that influence how tall each layer should be.
  Desired resolution: lower layer height should result in a print with less noticeable ribs or bands, overall less imperfections, as each layer is smaller. Aesthetics plays a role here, but also the type of model, for example, a mechanical part may not need such a high resolution finish, whereas a presentation piece may do so.
  Print speed: shorter layers will result in smoother print but each print will take longer, simply because the extruder must trace the patter more times. A later goal will be to strike a balance between layer height, the speed of printer, and the quality of the resulting print.

- **Fill density:** it's the percentage of each layer that will be filled in with plastic. The higher the density the more robust will be the final part.

- **Speed:** this parameter allows us to define the linear velocity of the extruder while it moves along the manufacturing platform to deposit the material. The speed is a really sensitive parameter because depending on which zone of the layer is being printed it can vary. For this reason, to make the experiment simpler some of this parameters have been previously set and are the same for all the configurations, excluding the ones regarding the perimeters of the part, infill, solid infill, top solid infill which are the ones that will define the properties in every case.

- **Orientation:** it determines the part manufacturing direction based on the coordinates system of the machine, meaning how the layers fall one on top of the other, which direction the extruded threads will have and of course in which direction the biggest unions will be placed.

3.1.2. Taguchi's experimental design

A correct design of experiments (DOE) is basic in order to get proper results on the effects of input variables (factors) against an output variable (response). The experiment consists in a series of tests in which predetermined changes have been done to the input variables. After every test the data is collected. The DOE is used to identify the conditions of the process and the parts of the product that affect the quality, so later determine the best factor configuration to optimize the results.

The input variables are the fabrication parameters previously chosen (Nozzle diameter, Layer height, Fill density, Speed and Orientation) and the output variable would be the calculations that we make with the data obtained through the tests.

Three levels have been chosen for each of the parameters in order to be able to obtain wider and more significant results regarding how much influence each of the input values have over the final part.

Because using a classic experiment design wouldn't be plausible, because with 5 factors with 3 levels each the number of experiments would be too high ($3^5=243$) and more over if we repeat each configuration 3 times ($243 \cdot 3=729$), it has been decided to use an alternative experimental design based on the statistical method of Taguchi, which reduces the number of tests needed but keeps the sturdiness of the final results like if we were using the classical method.

The Taguchi method uses an experimental plan which is represented by an orthogonal matrix that gives a certain amount of parameters to each test, this allows the experiment to still be effective while reducing the runs needed to obtain the same results we would by using the classical method.

Taguchi developed a series of particular arrangements that was denominated like the following expression:

$$a(b)^c$$

- ***a:*** *represents the number of tests that are going to be carried out. It's also the number of lines in the arrangement.*
- ***b:*** *represents the number of levels each factor will take.*
- ***c:*** *is the number of independent effects that can be studied. It's also the number of columns.*

The study will not only study each parameter on its own but it will also take into consideration the interaction between one another. For this reason and according to our needs the orthogonal arrangement that fits all this conditions is the L27(3)[13] one, because it can study 5 factors (A, B, C, D, E) and at the same time study the interaction between which we think are the three most important parameters (A-B; B-C; A-C) (Table 4.1).

		LEVELS				
FACTORS	**ASSIGNMENT**	**1**	**2**	**3**	**UNITS**	**COLUMN**
Nozzle Diameter	A	0,3	0,4	0,6	mm	1
Layer Height	B	0,1	0,2	0,3	mm	2
Fill Density	C	25	50	75	%	5
Speed	D	25	40	60	mm/s	9
Orientation	E	Z0	Z45	X90	º	10

Table 3.1: Parametersused in the Taguchi's experiment design, alongtheirassignedletters, units, columnsandthreelevels of study

The following linear image (Figure 4.1) shows the factors and how they interact with each other. Note that each dot has a number assigned and we have to ignore the ones which we haven't assigned a number to.

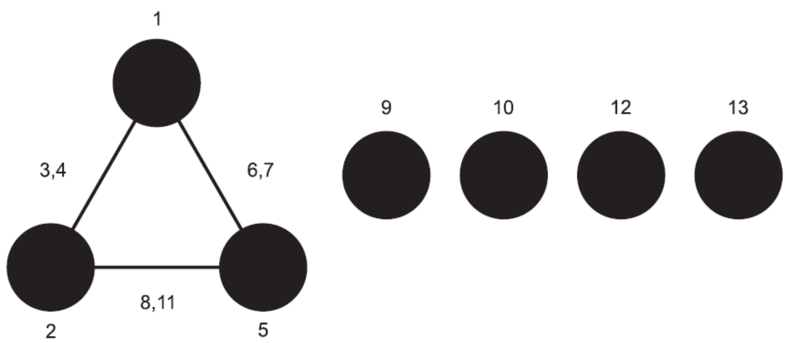

Figure 3.1.: L27(3)13 linear graph.

The manufacturing parameters studied A, B, C, D and E are assigned to the columns 1, 2, 5, 9 and 10. And the interactions A-B, B-C and A-C are assigned to the columns 3, 4, 6, 7, 8 and 11. Finally the columns 12 and 13 will be assigned to the experimental error. In the following table (Table 4.2) the full experiment design:

Factor	A	B	AxB	AxB	C	AxC	AxC	BxC	D	E	BxC	e	e
Column	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2

18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Table 3.2.: Project'sTaguchi's experimental design

3.2. Specimen's design and Manufacturing

The specimens used in the experiments were created following the norm UNE-EN-ISO-527-1=20012 (Determination of tensile properties for plastics). The size of them have been slightly modified to carry on the tests easier (Figure 4.2.). This shouldn't worry us because the specimens weren't normalized in the first place because the norm talks about solid parts and there is actually no norm that talks about parts filled with certain percentage of infill.

The specimens were designed using the CAD software SolidWorks and the printing parameters were assigned through the Slic3r software. The material used to manufacture the specimens was ABS and it were printed using the BCN3D+ model from the BCN3D technologies.

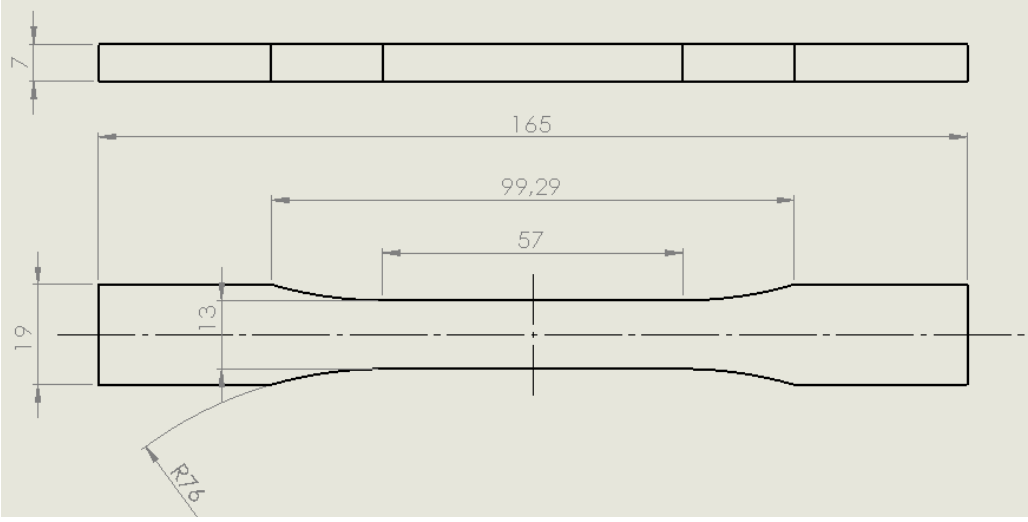

Figure 3.1: Specimen measures

3.2.1. Specimen's manufacturing parameterization

To be able to print the specimens the CAD file must be converted into .STL format. This converts every surface of the 3D model into tiny triangular surfaces, the smaller the triangles the higher quality the specimens will have.

Because sometimes the conversion between the 3D model and the STL format doesn't happen smoothly and there are some errors in the final part, an intermediate software called Netfabb has been used in order to previsualize, place correctly and repair the little problems that the specimen might have. Once the repair is finished the part will have to be exported into the STL format so that it is compatible with Slic3r.

Slic3r is the software that will allow to communicate the computer with the 3D printer. The most desired parameters can be modified in the computer using this software and then all of this can be exported to the 3D printer which will print the specimens according to our configurations.

As it has been mentioned previously the configurations are determined by the Taguchi's orthogonal arrangement (4.2.1. Taguchi's experiment design) and they assign a configuration to each set of specimens.

	Factor	A	B	C	D	E					
Naming	**Column**	**1**	**2**	**5**	**9**	**10**	Nozzle Diameter	Layer height	Fill Density	Speed	Orientation
ABS-0,3-0,1-25-35-0-TRAC	**1**	1	1	1	1	1	0,3	0,1	25	35	0
ABS-0,3-0,1-50-45-45-TRAC	**2**	1	1	2	2	2	0,3	0,1	50	45	45
ABS-0,3-0,1-75-60-360-TRAC	**3**	1	1	3	3	3	0,3	0,1	75	60	360
ABS-0,3-0,2-25-45-45-TRAC	**4**	1	2	1	2	2	0,3	0,2	25	45	45
ABS-0,3-0,2-50-60-360-TRAC	**5**	1	2	2	3	3	0,3	0,2	50	60	360
ABS-0,3-0,2-75-35-0-TRAC	**6**	1	2	3	1	1	0,3	0,2	75	35	0
ABS-0,3-0,3-25-60-360-TRAC	**7**	1	3	1	3	3	0,3	0,3	25	60	360
ABS-0,3-0,3-50-35-0-TRAC	**8**	1	3	2	1	1	0,3	0,3	50	35	0
ABS-0,3-0,3-75-45-45-TRAC	**9**	1	3	3	2	2	0,3	0,3	75	45	45
ABS-0,4-0,1-25-45-45-TRAC	**10**	2	1	1	2	3	0,4	0,1	25	45	45
ABS-0,4-0,1-50-60-360-TRAC	**11**	2	1	2	3	1	0,4	0,1	50	60	360
ABS-0,4-0,1-75-35-0-TRAC	**12**	2	1	3	1	2	0,4	0,1	75	35	0
ABS-0,4-0,2-25-60-360-TRAC	**13**	2	2	1	3	1	0,4	0,2	25	60	360
ABS-0,4-0,2-50-35-0-TRAC	**14**	2	2	2	1	2	0,4	0,2	50	35	0
ABS-0,4-0,2-75-45-45-TRAC	**15**	2	2	3	2	3	0,4	0,2	75	45	45
ABS-0,4-0,3-25-35-0-TRAC	**16**	2	3	1	1	2	0,4	0,3	25	35	0
ABS-0,4-0,3-50-45-45-TRAC	**17**	2	3	2	2	3	0,4	0,3	50	45	45

ABS-0,4-0,3-75-60-360-TRAC	**18**	2	3	3	3	1	0,4	0,3	75	60	360
ABS-0,6-0,1-25-60-360-TRAC	**19**	3	1	1	3	2	0,6	0,1	25	60	360
ABS-0,6-0,1-50-35-0-TRAC	**20**	3	1	2	1	3	0,6	0,1	50	35	0
ABS-0,6-0,1-75-45-45-TRAC	**21**	3	1	3	2	1	0,6	0,1	75	45	45
ABS-0,6-0,2-25-35-0-TRAC	**22**	3	2	1	1	3	0,6	0,2	25	35	0
ABS-0,6-0,2-50-45-45-TRAC	**23**	3	2	2	2	1	0,6	0,2	50	45	45
ABS-0,6-0,2-75-60-360-TRAC	**24**	3	2	3	3	2	0,6	0,2	75	60	360
ABS-0,6-0,3-25-45-45-TRAC	**25**	3	3	1	2	1	0,6	0,3	25	45	45
ABS-0,6-0,3-50-60-360-TRAC	**26**	3	3	2	3	2	0,6	0,3	50	60	360
ABS-0,6-0,3-75-35-0-TRAC	**27**	3	3	3	1	3	0,6	0,3	75	35	0

Table 3.3: Taguchi'sorthogonalarrangement

Even if the parameters shown in the previous table (Table 4.3) are the most important parameters and the ones that are going to be studied there are plenty more parameters that can be modified in the Slic3r software and can have an impact on the final result of the specimens. For this reason, the parameters not related to the study has been fixed so they have no influence on the final result of the experiment.

In the following images it can be seen each of the parameters that can be configured in the Slic3r software. The squares in red are the parameters that make unique every specimen. The images are from the specimen number 20: *ABS-0,6-0,1-50-25-X90-TRAC*, (Figures 4.3., 4.4., 4.5. and 4.6.).

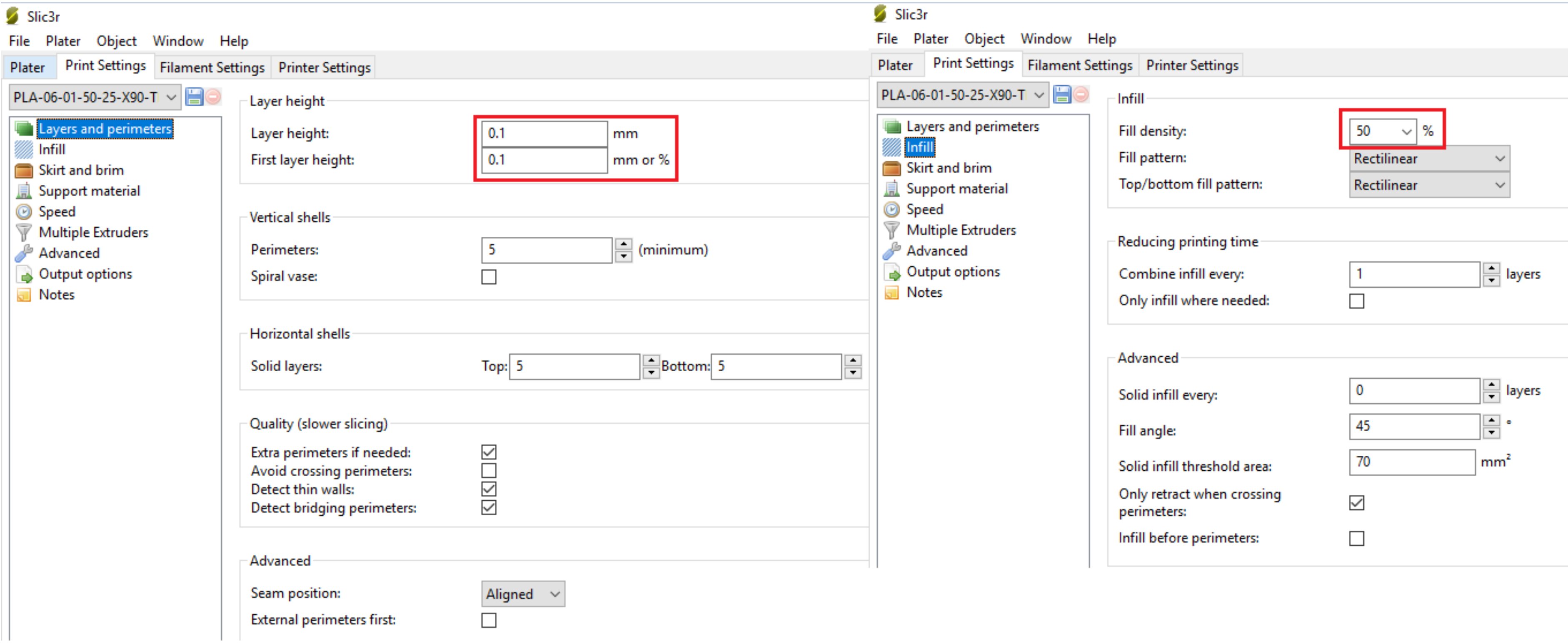

Figure 3.2.: Slic3r. Layer and perímetres

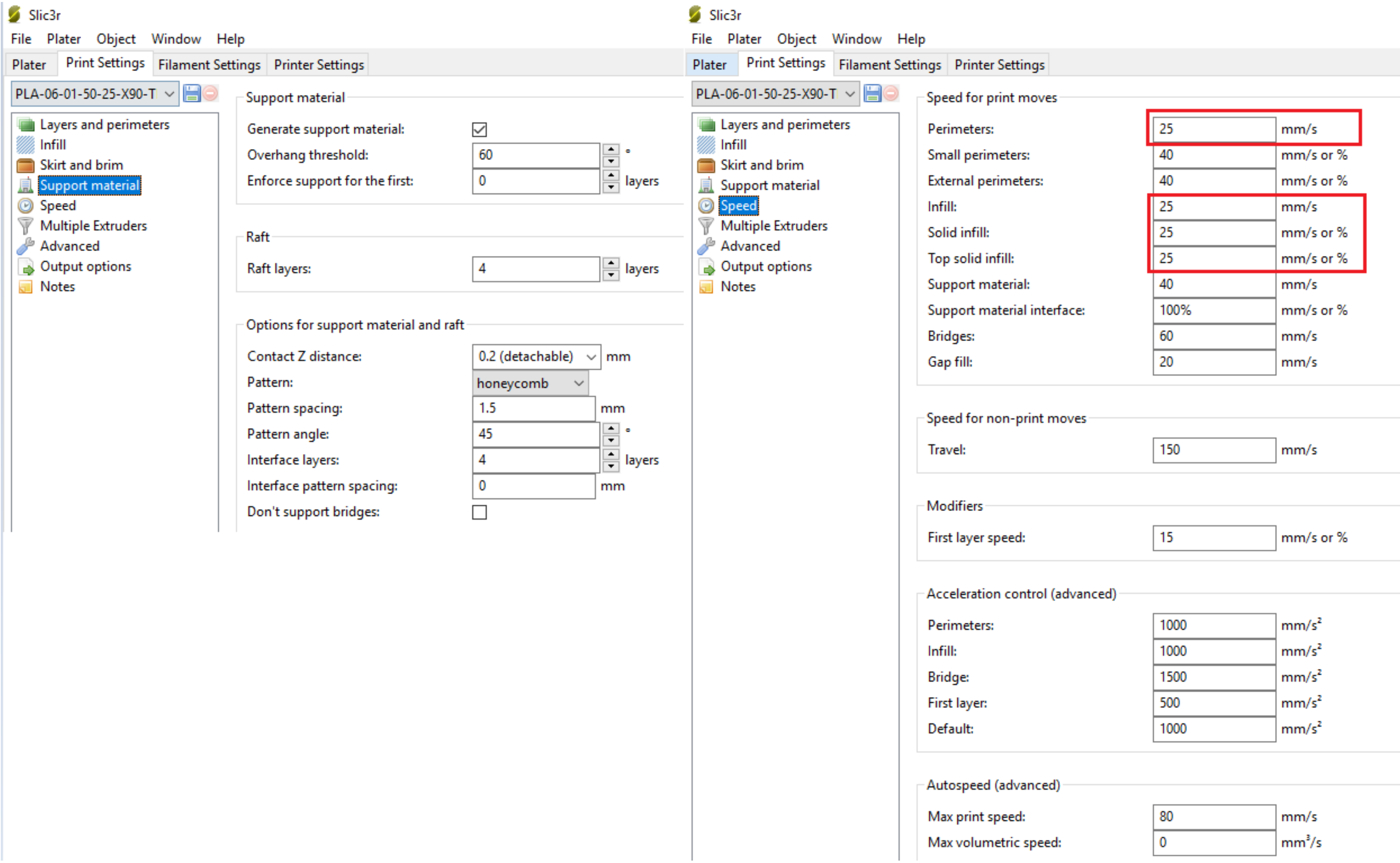

Figure 3.3: Slic3r. Support material

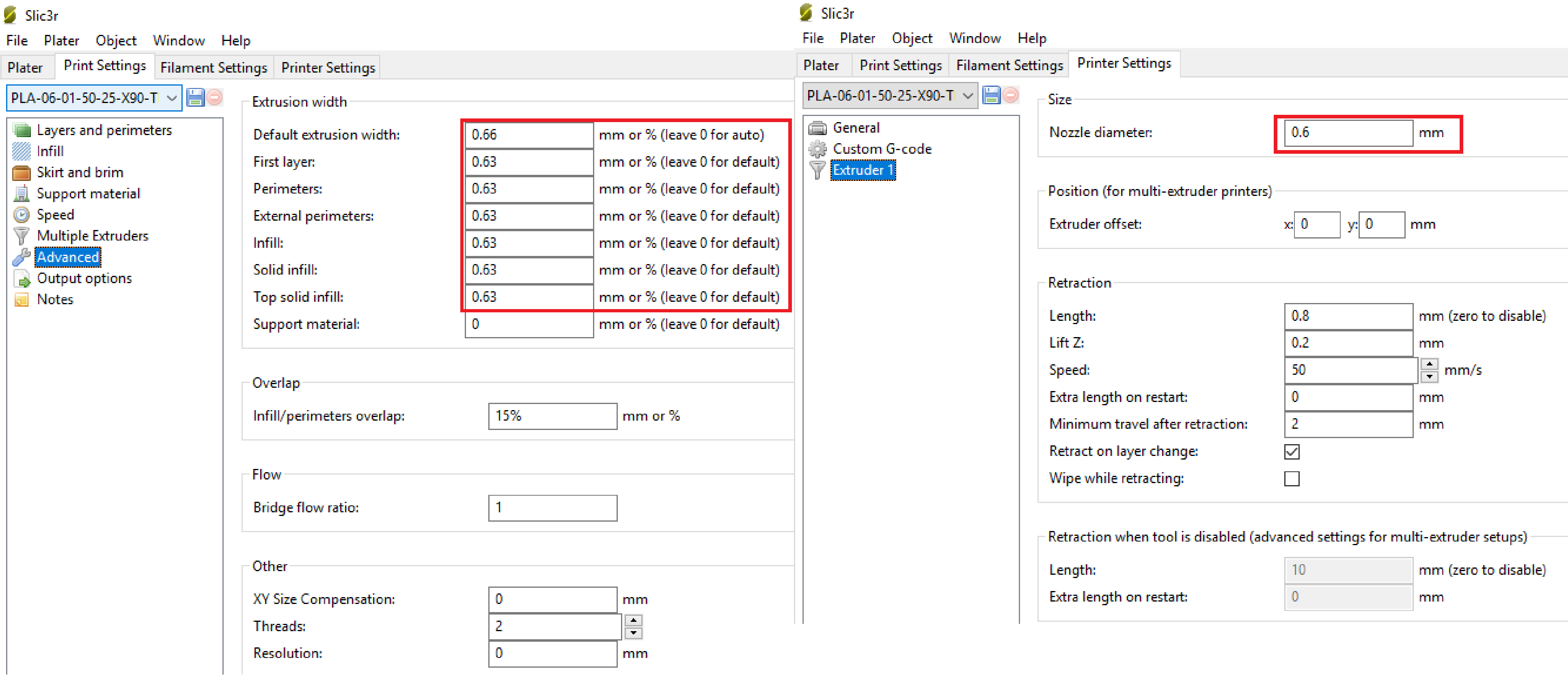

Figure 3.4: Slic3r. Advanced

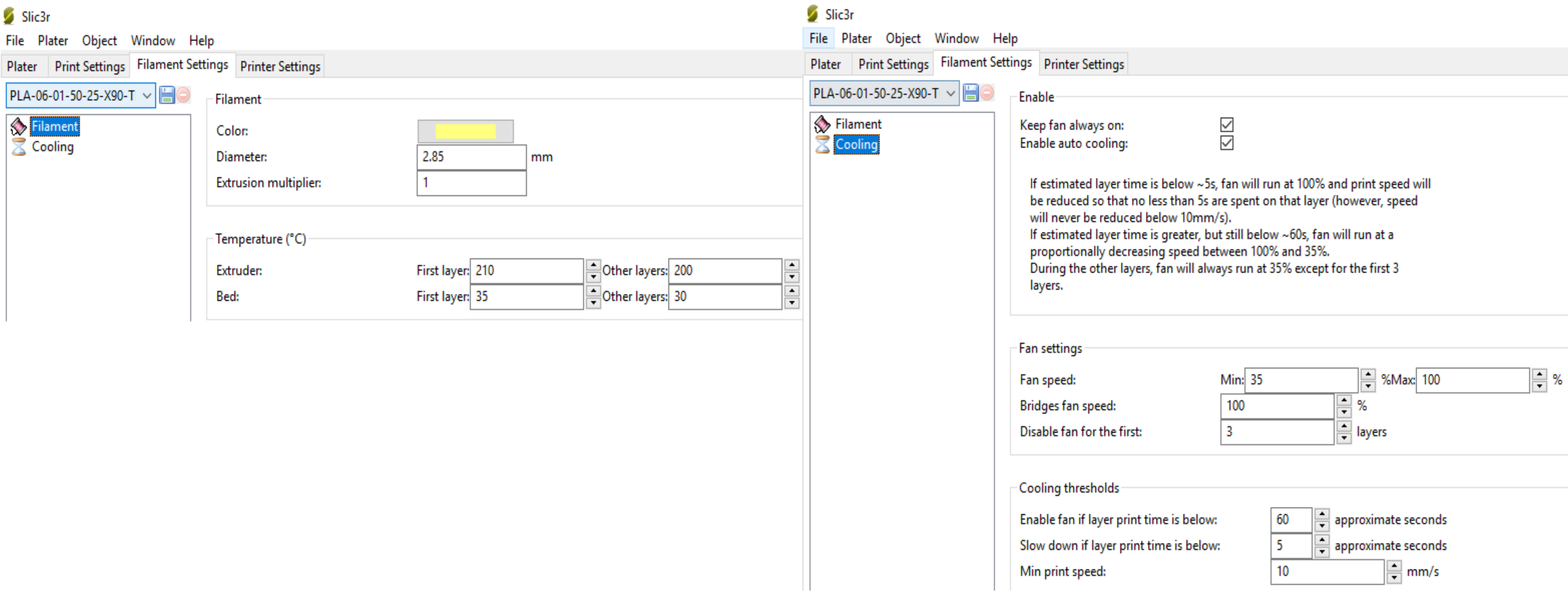

Figure 3.5: Slic3r. Filament

The only remark left to make after talking about the parameters and seeing them on the previous figures is that there are three values that have to be changed for every nozzle diameter. For a 0,3mm nozzle the Extrusion Width takes the value 0,35mm, for a 0,4mm nozzle it takes a 0,42mm value and for a 0,6mm nozzle it takes a value of 0,66mm (this one can be seen in the figure 4.5.). Even if it has been said that the only parameters that would be modified would be the specified in by the Taguchi's configuration, this values are directly related to the nozzle diameter. This means that the flow of material has to be modified when modifying the nozzle diameter in order to have an optimal printing.

After configuring the specimen with Slic3r and setting the printing direction we will export the document as G-code. This format contains the list of instructions or movements the 3D printer will have to do in order to print the part in the desired configuration.

The G-code can be introduced in the 3D printer in a variety of ways. In this case an SD card has been used to load the G-code into the printer.

3.3. Experiment procedure

The experiment procedure for the 81 specimens will be made the same in order to make sure there are no changes in the steps taken for each of the tests.

Every test consists on submitting each specimen to a traction force that will lengthen its size along the vertical axis using a constant speed (1mm/min) until it breaks. The lengthening as well as the force applied will be saved in order to study the data obtained.

The machine used to carry on the experiments is the Microtest EM2/20 equipped with a 25kN capacity power cell. The data is recorded using both the Microtest internal software and the Spider data acquisition system, two S1 pneumatic jaws and the Microtest SCM3000-Catman 4.5 control software (Figure 4.7.).

Figure 3.6: Microtest EM2/20 universal test machinedandtheacquisition data system.

Each specimen will be places perfectly perpendicular to the floor between the superior and the inferior jaw. The superior jaw is fixed while the inferior does all the force downwards. The specimen is forced to deformed because it is submitted to a constant traction force at a constant speed (1mm/min). The Spider data acquisition system has been added because of its precision at data gathering.

The force is read using the power cell and the lengthening comes from the extensometers attached to the specimen before starting the experiment (Figure 4.8.).

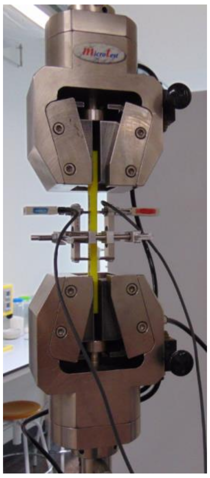

Figure 3.7: Assembly of jaws, specimenandextensometers.

3.4. Excel sheet calculations

When each test is finished we will extract the data from computer and introduced it to an Excel sheet where the characteristic curve of the stress-strain behaviour will be obtained. This same sheet will give us the elastic modulus, maximum tension, maximum length, resilience modulus and tenacity modulus.

3.4.1. Data import

Once the data from the Spider software have been obtained (Data Logger), it is necessary to convert the data to be able to work with it.

From the software data format, a reconstruction oriented into an Excel data document has to be made (adequate software to work with data sheets).

Next, there are the steps that have to be followed to convert the data in order to be able to work with it in an Excel data sheet:

1. Open Excel software.
2. Menu File- Open- All Files (*.*)-select...
3. Select the file where the test data is saved in. The file contains the specimen elongation, the mean of the elongation calculated by the two extensometers, the applied force at every moment of the test.
4. The Wizard to import the text will open:

   - Step 1 out of 3:

     Delimited

     Start to import at row 1

     Windows ANSI source file

     Next

   - Step 2 out of 3:

Tab dividers; semi-colon.

Text Qualifier (“)

Next

- Step out of 3:

  General

  Advanced

  Decimal Separator (,)

  Separate from thousands (.)

  Finalize

Then all the data has to be arranged:

1. Eliminate the first rows where the force values are negative.
2. Eliminate the last rows where the load drops drastically.
3. In some cases, during the data acquisition the extensometers slip and some data is incoherent in some intervals. This defect has been noted in a notebook during the tests this way they can be corrected in the Excel sheet.

The excel sheet will give us the values of the parameters needed to analyse the mechanical properties of the specimens.

Once this work has been done for each of the specimens a register will be created to calculate the mean values of all the results. This final results or output parameters will allow to make the Taguchi’s statistical analysis to be able to extract the conclusions related to the manufacturing parameters and the influence that they have on the mechanical traction resistance property of the ABS specimens created through FFF.

An exhaustive protocol procedure is attached to the annex (Annex 2) created for the sole purpose of making this experiment as accurate as possible. Moreover, there is another section in the annex which contains the theory behind the Excel (Annex 3) calculations and the procedure that has to be followed to obtain these results.

4. Statistical analysis

Once the data from all the specimens has been calculated using the excel sheets, the Minitab software will be used in order to obtain all the result tables from the lineal model and all the graphs associated to it, which will show the behavior of the parameters in front of the obtained data. The tables and graphs are going to be focused on the following information:

- Main effects for Means, which will show how each factor affects the mean value of the resulting parameter and how important it is.

- Interaction for Means, which will show if any of the three main factors (Nozzle diameter, Layer height, Fill density) has any effect on the mean value while combined with each other.

- Main effects for SN Relations which references the value of the desired property and the noise to its variability. In our case the bigger each factor can make the final result of each property the better.

- Interactions for SN Relations which will show if any of the three main factors has any effect on making the end value higher when combined with each other.

Apart from all the data mentioned before, Minitab also executes an ANOVA analysis in order to evaluate the relevance of each of the factors studied when compared to the mean values of the response variable (out-parameter) in their different levels (3 per parameter). The significance level is 5% (α=0,05) which means that for a fabrication parameter to be statistically meaningful its p-value will have to be inferior to 0,05.

The data obtained from the excel sheets and afterwards introduced to the Minitab software will be shown at the beginning of each of the sections to show where the Minitab's results come from. The data is formed by the results of each of the 3 specimens per configuration (27 configurations total) broken during the tests.

4.1. Young's module

This section will study the influence that the manufacturing parameters have over the out-parameter Young's module (Table 5.1).

Young's Module E(Gpa)						
Name	**1**	**2**	**3**	**Mean Value**	**Standard Deviation**	**Error**
ABS-0,3-0,1-25-25-Z0-TRAC	2,105190298	1,954516546	2,295484322	**2,118397055**	**0,170867112**	**0,424457435**
ABS-0,3-0,1-50-40-Z45-TRAC	2,916281908	3,265875422	2,800543217	**2,994233515**	**0,242261956**	**0,60181206**

ABS-0,3-0,1-75-60-X90-TRAC	4,08385862	4,058451355	4,221543517	**4,121284497**	**0,087751271**	**0,217986242**
ABS-0,3-0,2-25-40-Z45-TRAC	2,437242354	2,214564863	2,354687314	**2,335498177**	**0,112572126**	**0,279644663**
ABS-0,3-0,2-50-60-X90-TRAC	3,332667268	3,054357315	3,433873214	**3,273632599**	**0,196524549**	**0,488194044**
ABS-0,3-0,2-75-25-Z0-TRAC	3,321308313	3,114687655	3,235879765	**3,223958578**	**0,103824901**	**0,257915353**
ABS-0,3-0,3-25-60-X90-TRAC	2,271108683	1,998351357	2,638735435	**2,302731825**	**0,321361104**	**0,798305238**
ABS-0,3-0,3-50-25-Z0-TRAC	2,795441149	2,456987566	2,751745646	**2,668058120**	**0,184093478**	**0,457313551**
ABS-0,3-0,3-75-40-Z45-TRAC	3,151238881	3,512358735	2,999668754	**3,221088790**	**0,263385671**	**0,654286278**
ABS-0,4-0,1-25-40-X90-TRAC	3,364313446	3,054689732	3,138735436	**3,185912871**	**0,160112441**	**0,397741353**
ABS-0,4-0,1-50-60-Z0-TRAC	2,643657136	2,453843513	2,90013838	**2,665879676**	**0,223975798**	**0,556386727**
ABS-0,4-0,1-75-25-Z45-TRAC	3,247282955	3,183873544	3,498734874	**3,309963791**	**0,166526513**	**0,413674792**
ABS-0,4-0,2-25-60-Z0-TRAC	2,187067354	1,805345839	2,195348738	**2,062587310**	**0,222816127**	**0,553505943**
ABS-0,4-0,2-50-25-Z45-TRAC	2,30111389	2,000867454	2,438438434	**2,246806592**	**0,223783495**	**0,555909019**
ABS-0,4-0,2-75-40-X90-TRAC	3,531727366	3,187543587	3,714358734	**3,477876563**	**0,267504171**	**0,6645172**
ABS-0,4-0,3-25-25-Z45-TRAC	2,385003077	1,998743574	2,568738739	**2,317495130**	**0,290932319**	**0,722715945**
ABS-0,4-0,3-50-40-X90-TRAC	2,602845199	2,138735435	2,54873574	**2,430105458**	**0,253780074**	**0,630424652**
ABS-0,4-0,3-75-60-Z0-TRAC	2,871439731	2,483735435	3,438873834	**2,931349667**	**0,480379267**	**1,193328254**
ABS-0,6-0,1-25-60-Z45-TRAC	2,867563256	2,883874354	3,008734359	**2,920057323**	**0,077228398**	**0,191845976**
ABS-0,6-0,1-50-25-X90-TRAC	4,374595213	3,999387387	4,521838739	**4,298607113**	**0,269387262**	**0,669195057**
ABS-0,6-0,1-75-40-Z0-TRAC	3,741256689	3,641438738	4,013213584	**3,798636337**	**0,192414792**	**0,47798484**
ABS-0,6-0,2-25-25-X90-TRAC	3,987514236	3,583487387	4,211384344	**3,927461989**	**0,318226886**	**0,790519409**
ABS-0,6-0,2-50-40-Z0-TRAC	3,512672322	3,068768735	3,748645844	**3,443362300**	**0,345197233**	**0,857517465**
ABS-0,6-0,2-75-60-Z45-TRAC	3,298523341	3,655435434	3,043848438	**3,332602404**	**0,30721442**	**0,763162927**
ABS-0,6-0,3-25-40-Z0-TRAC	3,281222452	2,813543874	3,598384354	**3,231050227**	**0,394818419**	**0,980783324**
ABS-0,6-0,3-50-60-Z45-TRAC	3,101268923	2,768735435	3,523973844	**3,131326067**	**0,378515306**	**0,940284147**
ABS-0,6-0,3-75-25-X90-TRAC	3,600363895	3,018435436	3,438735435	**3,352511589**	**0,300393237**	**0,746218167**

Table 4.1: Mean values of the out-parameters of the Young's module for each of the configurations of the Taguchi's orthogonal arrangement

4.1.1. Main effects for means

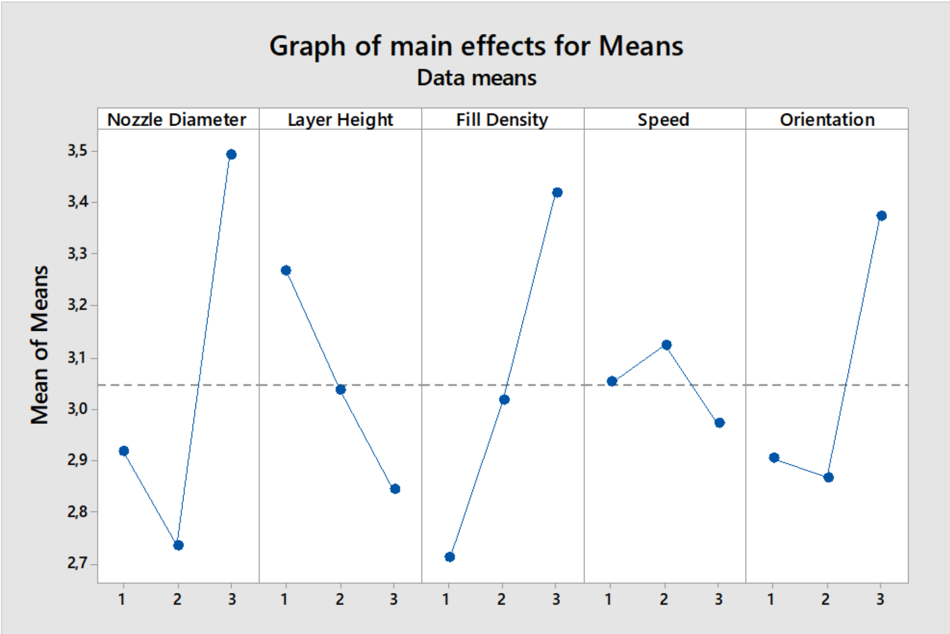

Figure 4.1: Main effects of the manufacturing parameters over the mean values of the Young's Module

As it can be seen in the figure 5.1. the Nozzle diameter seems to be the parameter that has a bigger effect when reaching its maximum value. Even though it slightly decreases from the first level to the second, when reaching its third level (diameter 0,6mm) it drastically raises the mean value of the Young's module. It seems to be happening the same with the Orientation factor even though in a lesser proportion.

The other factor that seems to always contribute to the growth of the Young's module when its levels raise is the Fill Density, which makes sense. The higher the specimen is filled with material, the harder it is for it to deform and thus the higher the Young's module will be.

Regarding the Speed, it is not clear which pattern it is following because it behaves better when making the speed higher from the first to the second level but drops its performance when making it higher from the second to the third level.

Finally, it seems like augmenting the layer height value affects negatively to the value of the Young's Module.

Variance Analysis for Means	
Source	p-value

Nozzle Diameter	0,012
Layer Height	0,091
Fill Density	0,018
Speed	0,593
Orientation	0,039

Response table for Means

Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	2,918	3,268	2,711	3,051	2,905
2	2,736	3,036	3,017	3,124	2,868
3	3,493	2,843	3,419	2,971	3,374
Delta	0,756	0,425	0,708	0,153	0,507
Rank	1	4	2	5	3

Table 4.2: Level of importance and p-values of the different out-parameters related to the Young's module mean value

As mentioned before, the graph is only a visual representation of the effect each parameter has on the specific result, in this case the Young module. As it can be observed in the table 5.2, the statistical ANOVA analysis confirms that the Nozzle Diameter, Fill Density and Orientation have a significant influence over the elasticity of the material in this order of relevance (p-value<0,05).

4.1.2. Interaction for the Means

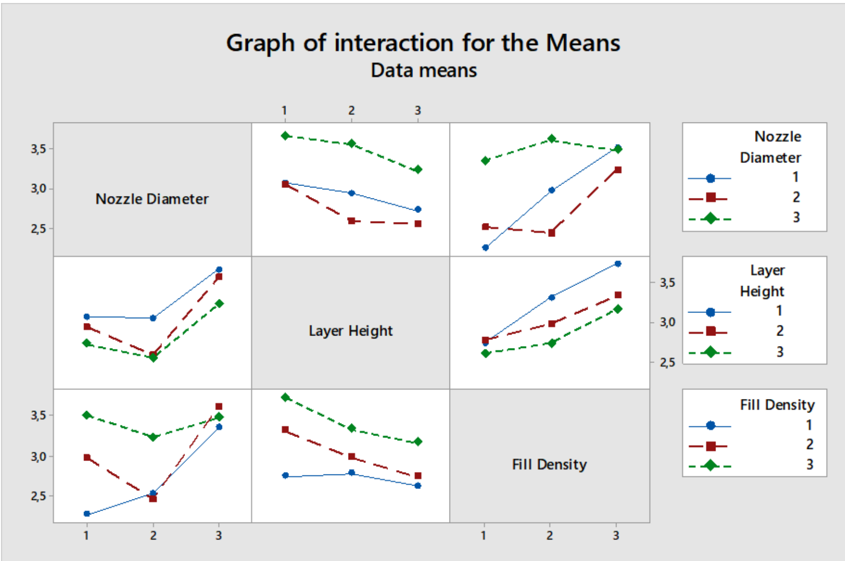

Figure 4.2: Interaction between parameters and relevance on the mean result of the Young's module

When the effect of a value or manufacturing parameter in this case depends on another factor it means that they interact with each other. One independent value has an interaction with another independent value when one has an effect over the other and vice versa.

In the Figure 5.2 the interactions between factors are shown by the different lines. When the lines are parallel with each other it means that no interaction exists, on the other hand if the cross it means that it might be an interaction. The bigger the inclination on the lines while crossing the bigger the possibility that it exists an interaction. Not because they cross it is assured an interaction to exist or to be relevant.

For the interaction to exist the p-value of the interaction has to be lower than 0,05 for the interaction to be statistically relevant. In the table 5.3 the p-values of the interaction between parameters can be read.

Interaction for Mean's variance analysis	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,818
Nozzle Diameter vs Fill Density	0,103
Layer Height vs Fill Density	0,629

Table 4.3: P-value of the interactions between manufacturing parameters

As it can be seen in the table, there is not an existing interaction or at least an existing relevant interaction between the nozzle diameter, the layer height or the fill density that can influence one another and affect the mean value of the out-parameter Young module.

4.1.3. Main effects for SN Relations

The signal-to-noise ratio is a measure of robustness that is used to identify the manufacturing parameters that reduce the variability of tests or experiments (in our case traction tests) when minimizing the effects of the non-controllable factors, like the out-parameters extracted from the traction test. These robust parameters are really useful in manufacturing because it allows to know which manufacturing parameters are more important in their influence over the factors that can't be controlled but we want to improve.

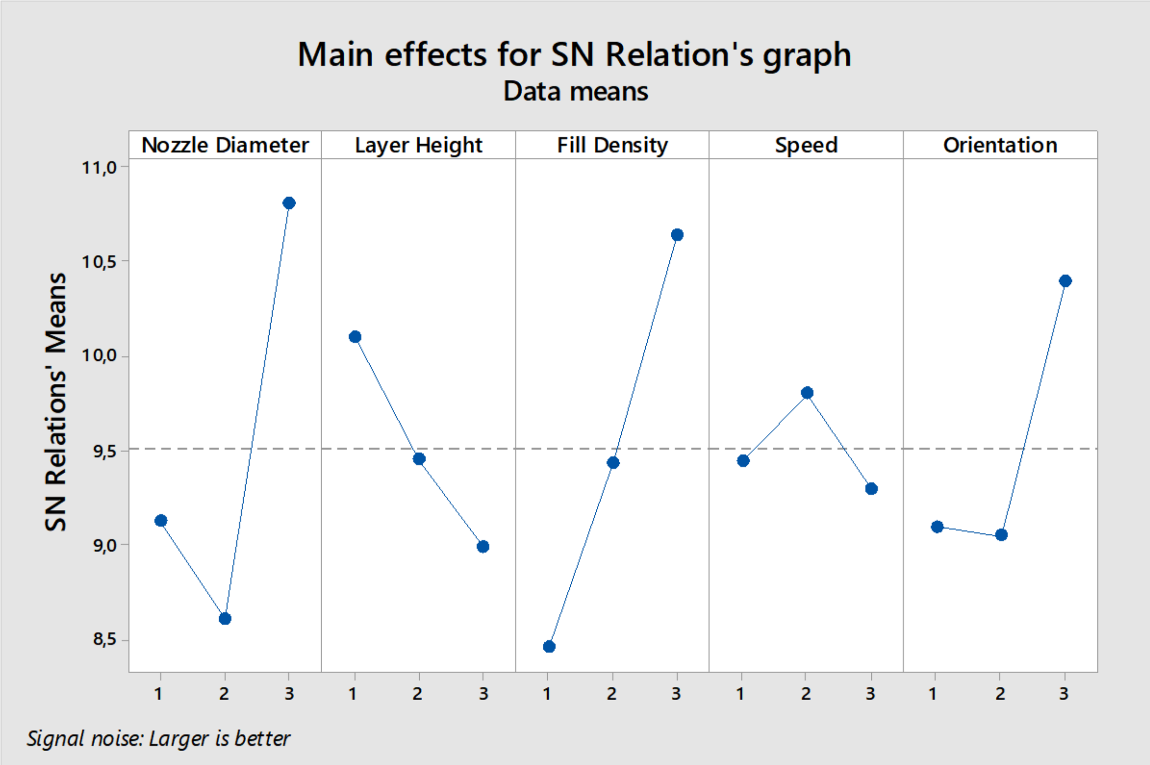

Figure 4.3: Main effects of the manufacturing parameters for the SN Relations over the Young's module mean value

As it is apparent in the Figure 5.3, the Fill Density is the only parameter that grows in each of its levels, making it a clear candidate to be a robust parameter. The Orientation seems to be stationary between the first and second levels but suffers a big growth when switching to its third level.

The Nozzle Diameter suffers a slight decrease from the first level to the second soon to be followed by the biggest growth when changing to its third level.

Lastly, the Layer Height seems to decrease while its levels go up and the speed behaves up and down when changing to 45 mm/s to 60 mm/s.

Variance Analysis for SN relations	
Source	**p-value**
Nozzle Diameter	0,01
Layer Height	0,101
Fill Density	0,012
Speed	0,471
Orientation	0,04

SN relations response's table					
Level	Nozzle Diameter	Layer Height	Fill Density	Speed	Orientation
1	9,123	10,099	8,463	9,444	9,097
2	8,609	9,451	9,437	9,797	9,051
3	10,806	8,988	10,639	9,297	10,39
Delta	2,197	1,111	2,176	0,501	1,338
Rank	1	4	2	5	3

Table 4.4: P-values of the SN relations for the manufacturing parameters regarding the Young's module out-parameter

As hinted by the 5.4 graph the only parameters statistically relevant and robust regarding the Young's module results are the Nozzle Diameter, the Fill Density and the Orientation in this same order shown by the table 5.4.

4.1.4. Interaction for SN Relations

This part of the study will allow us to know how robust the interactions between parameters are when trying to maximize the value of the out-parameter, in this case the Young module. The robustness of these relations will show if any relations between the three main manufacturing parameters (Nozzle diameter, Layer height and Fill density) have a real influence or on the other hand it is the noise which is the responsible of the interaction when there isn't really one.

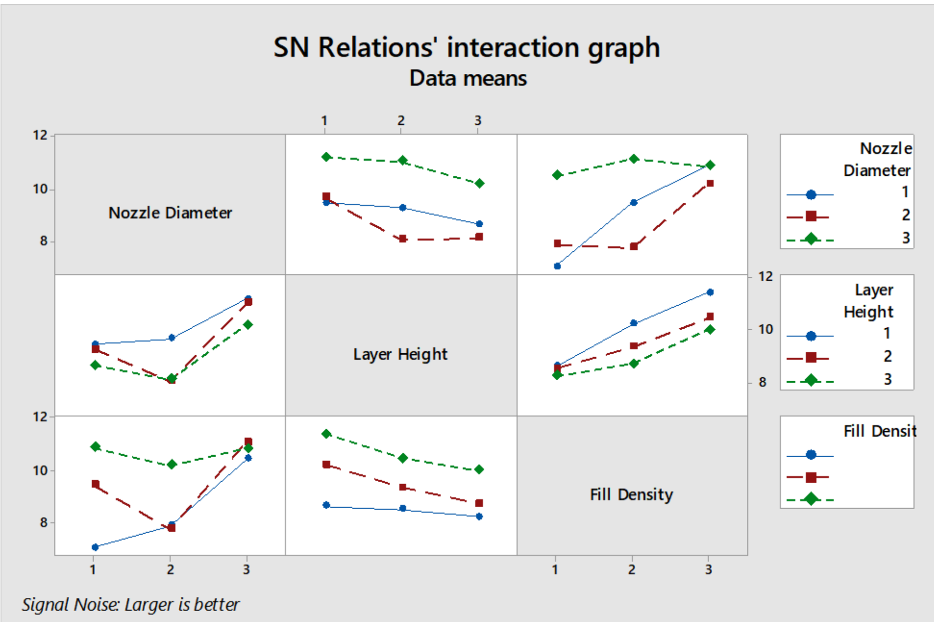

Figure 4.4: Interactions for SN Relations between manufacturing parameters regarding the Young module out-parameter

Variance's Analysis for SN Relations Interactions	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,576
Nozzle Diameter vs Fill Density	0,074
Layer Height vs Fill Density	0,745

Table 4.5: P-values of the SN Relations between the manufacturing parameters regarding the Young module out-parameter

As it can be seen in the graph 5.4 the only possible interaction between parameters would be the one between the Nozzle Diameter and the Fill Density. This possible interaction is denied by its statistical relevance. The p-value of the interaction in the table 5.5 is greater than 0,05 and for this reason it is considered invalid. It can be said that there is not a robust interaction between any of the parameters that can influence the Young module.

4.2. 0,2% Offset Yield Strength

This section will study the influence that the manufacturing parameters have over the out-parameter 0,2% Offset Yield Strength.

0,2% Offset Yield Strength Rp0,2 (Mpa)						
Name	**1**	**2**	**3**	**Mean Value**	**Standard Deviation**	**Error**
ABS-0,3-0,1-25-25-Z0-TRAC	12,44102849	12,16874	12,96874	**12,52616647**	**0,406738673**	**1,010395**
ABS-0,3-0,1-50-40-Z45-TRAC	15,14449549	15,83573	14,63873	**15,20632146**	**0,600890152**	**1,492694**
ABS-0,3-0,1-75-60-X90-TRAC	23,575028	23,03874	23,42387	**23,34588006**	**0,276520831**	**0,686916**
ABS-0,3-0,2-25-40-Z45-TRAC	13,5857736	12,93874	13,65397	**13,39282896**	**0,394728484**	**0,98056**
ABS-0,3-0,2-50-60-X90-TRAC	17,68979556	18,00384	17,43873	**17,71078845**	**0,283134832**	**0,703346**
ABS-0,3-0,2-75-25-Z0-TRAC	17,97742395	18,53873	18,03874	**18,18496574**	**0,307902824**	**0,764873**
ABS-0,3-0,3-25-60-X90-TRAC	11,50181068	11,73874	11,9439	**11,72814893**	**0,221233508**	**0,549574**
ABS-0,3-0,3-50-25-Z0-TRAC	13,43741694	13,48387	13,99868	**13,63998918**	**0,311499806**	**0,773808**
ABS-0,3-0,3-75-40-Z45-TRAC	17,39389335	17,01837	17,32357	**17,24528037**	**0,199627462**	**0,495902**
ABS-0,4-0,1-25-40-X90-TRAC	16,51204363	16,31369	16,18375	**16,33649511**	**0,165328789**	**0,410699**
ABS-0,4-0,1-50-60-Z0-TRAC	14,99551434	15,11874	14,99387	**15,03604221**	**0,071621994**	**0,177919**
ABS-0,4-0,1-75-25-Z45-TRAC	16,42000241	16,63874	16,13873	**16,39915746**	**0,250651373**	**0,622653**

ABS-0,4-0,2-25-60-Z0-TRAC	10,84953305	10,36387	10,93875	**10,71738693**	**0,309384814**	**0,768554**
ABS-0,4-0,2-50-25-Z45-TRAC	11,15424244	11,00044	10,84387	**10,99951824**	**0,155186495**	**0,385505**
ABS-0,4-0,2-75-40-X90-TRAC	18,05577017	17,81483	17,75399	**17,87486403**	**0,159595951**	**0,396458**
ABS-0,4-0,3-25-25-Z45-TRAC	11,45489603	11,00321	11,35468	**11,2709308**	**0,237202821**	**0,589244**
ABS-0,4-0,3-50-40-X90-TRAC	12,51944925	12,32199	12,51118	**12,45087185**	**0,111693855**	**0,277463**
ABS-0,4-0,3-75-60-Z0-TRAC	14,4322249	14,08744	14,22539	**14,24834924**	**0,173537831**	**0,431092**
ABS-0,6-0,1-25-60-Z45-TRAC	14,21336588	13,99939	14,01999	**14,0775803**	**0,118043998**	**0,293238**
ABS-0,6-0,1-50-25-X90-TRAC	25,75532695	25,41387	25,83874	**25,66931195**	**0,225112915**	**0,559211**
ABS-0,6-0,1-75-40-Z0-TRAC	20,96537533	20,57684	20,81112	**20,78444196**	**0,195638456**	**0,485993**
ABS-0,6-0,2-25-25-X90-TRAC	26,02156227	25,84387	26,10023	**25,98855624**	**0,131328554**	**0,326238**
ABS-0,6-0,2-50-40-Z0-TRAC	20,13628226	19,89554	20,32688	**20,11956697**	**0,216151376**	**0,53695**
ABS-0,6-0,2-75-60-Z45-TRAC	21,96523125	21,61387	21,72577	**21,76829108**	**0,17949705**	**0,445895**
ABS-0,6-0,3-25-40-Z0-TRAC	21,87452432	21,66654	21,41387	**21,65164563**	**0,230686084**	**0,573056**
ABS-0,6-0,3-50-60-Z45-TRAC	19,99656216	19,73435	20,13851	**19,95647561**	**0,205041294**	**0,509351**
ABS-0,6-0,3-75-25-X90-TRAC	26,85632972	26,80354	26,75139	**26,80375365**	**0,052471334**	**0,130346**

Table 4.6: Mean values of the out-parameters of the 0,2% Offset Yield Strength for each of the configurations of the Taguchi's orthogonal arrangement

4.2.1. Main effects for means

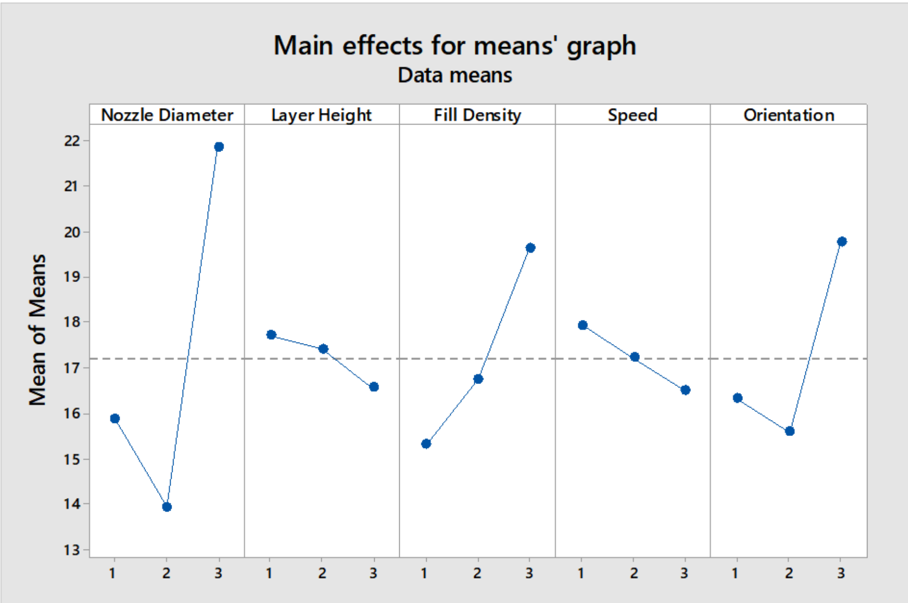

Figure 4.5: Main effects of the manufacturing parameters over the mean values of the 0,2% Offset Yield Strength

As it happened in the precious section with the Young's module, the graph 5.5 shows that the Nozzle Diameter seems to have the biggest impact on the mean of the 0,2% Offset Yield Strength, at least when changing from the second level to the third (from 0,4mm nozzle to 0,6mm). The Orientation seems to follow the same path as the Nozzle Diameter but in a lower scale, this might be because when printing in the X90 orientation the laying of the filaments must make them act as reinforcement fibers. Moreover, the Fill Density shows a raising trend through all of its levels, this is only normal like in the previous section, the more fibers and material the specimens have, the higher their resistance to breaking is.

The Layer Height and Speed show decreasing trends. It seems only normal in the case of the speed, the faster the printing the least precise and more error or mistakes can happen during the process making the final part less resistant to the traction forces.

Variance Analysis for Means	
Source	**p-value**
Nozzle Diameter	0,002
Layer Height	0,496
Fill Density	0,023
Speed	0,391
Orientation	0,022

Response table for Means					
Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	15,89	17,71	15,3	17,94	16,32
2	13,93	17,42	16,75	17,23	15,59
3	21,87	16,56	19,63	16,51	19,77
Delta	7,94	1,15	4,33	1,43	4,18
Rank	1	5	2	4	3

Table 4.7: Level of importance and p-values of the different out-parameters related to the 0,2% Offset Yield Strength mean value

As shown in the 5.7 table, the relevant parameters as intuited in the 5.6 figure are the Nozzle Diameter, the Orientation and the Fill Density in this order. This is because all their p-values are inferior to 0,05.

4.2.2. Interaction for the Means

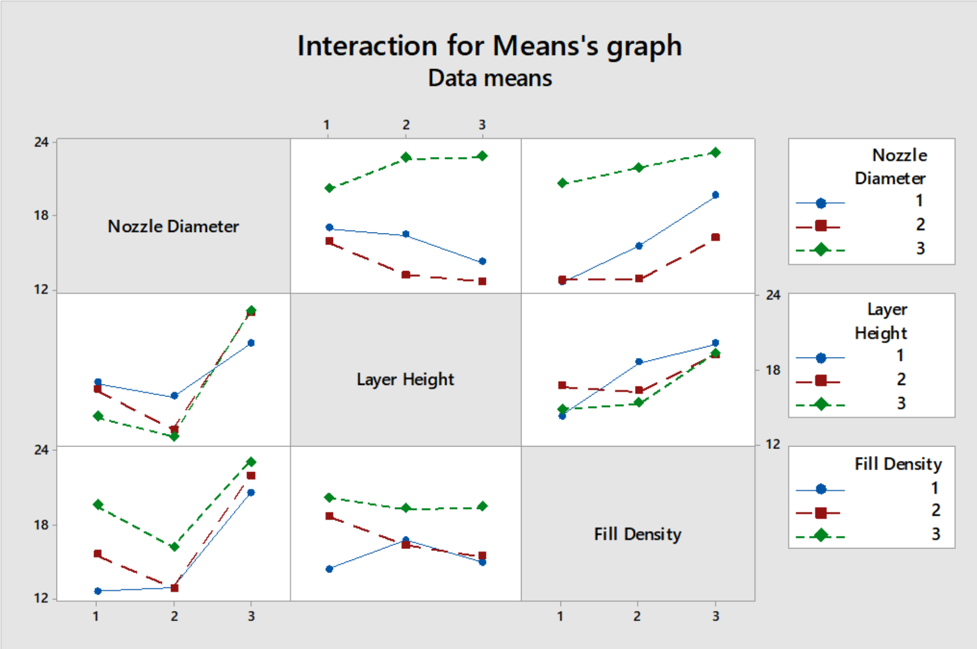

Figure 4.6: Interaction between parameters and relevance on the mean result of the 0,2% Offset Yield Strength

According to the graph 5.6 the only possible meaningful interactions between parameters can be between the nozzle Diameter and Layer Height and the one between the Layer Height and the Fill Density.

Interaction for Mean's variance analysis	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,174
Nozzle Diameter vs Fill Density	0,353
Layer Height vs Fill Density	0,6

Table 4.8: 1 P-value of the interactions between manufacturing parameters

The table 5.8 shows that the interaction between all the parameters are meaningless because its p-value is higher than the value set by the 5% significance level (0,05). Not a single interaction between parameters is robust enough to say that they have a solid influence in the final mean value of the 0,2% Offset Yield Strength.

4.2.3. Main effects for SN Relations

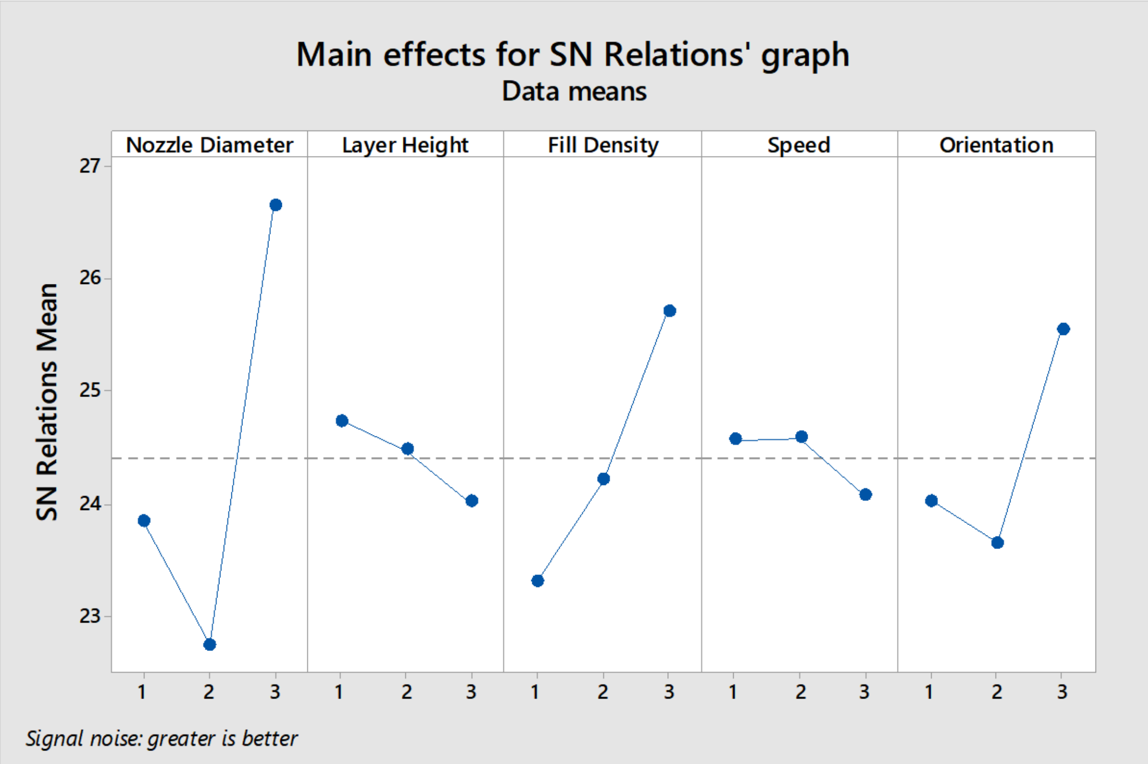

Figure 4.7: Main effects of the manufacturing parameters for the SN Relations over the 0,2% Offset Yield Strength mean value

The design factors that allow bigger SN design index are the parameters considered as robust and these are the ones that should be taken into account when manufacturing because they don't affect or minimally affect the characteristics of the end result.

In this case, according to the Figure 5.7, the Nozzle Diameter seems to be the most robust parameter. Even though it suffers a decline from changing from 0,3mm nozzle to 0,4mm nozzle, when changing from 0,4mm to 0,6mm it grows immensely. The Orientation seems to follow the same path as the Nozzle Diameter but in a smaller scale.

The Fill Density parameter shows a growing trend along all its three levels. It has a similar scale as the Orientation but it could be a real candidate to be a robust parameter.

The Layer Height and Speed show a decrease when going up in their levels. It seems only normal in the case of the speed because as mentioned before, the faster the fabrication, the more errors and mistakes can occur to the physical integrity of the part.

Variance Analysis for SN relations					
Source		**p-value**			
Nozzle Diameter		0,003			
Layer Height		0,413			
Fill Density		0,019			
Speed		0,55			
Orientation		0,036			
SN relations response's table					
Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	23,83	24,73	23,31	24,56	24,02
2	22,73	24,48	24,2	24,58	23,64
3	26,66	24,01	25,71	24,07	25,55
Delta	3,92	0,72	2,4	0,51	1,91
Rank	1	4	2	5	3

Table 4.9: P-values of the SN relations for the manufacturing parameters regarding the 0,2% Offset Yield Strength out-parameter

As seen i the 5.9 table, and as suspected, the robust and meaningful values are the Nozzle Diameter, the Fill Density and the Orientation. The response table also give us the values to know which are the better levels inside each meaningful parameter in order to get a better out-parameter. The higher the number, the better.

From the three robust parameters we would choose the third level of the Nozzle Diameter (0,6mm nozzle diameter), the third level from the Fill Density (75% fill density) and the third level from the Orientation (X90 orientation). Finally, from the two irrelevant parameters we would choose any of the options keeping in mind that we could base our choosing on if they will make our part cheaper or if they will make our part look better for example.

4.2.4. Interaction for SN Relations

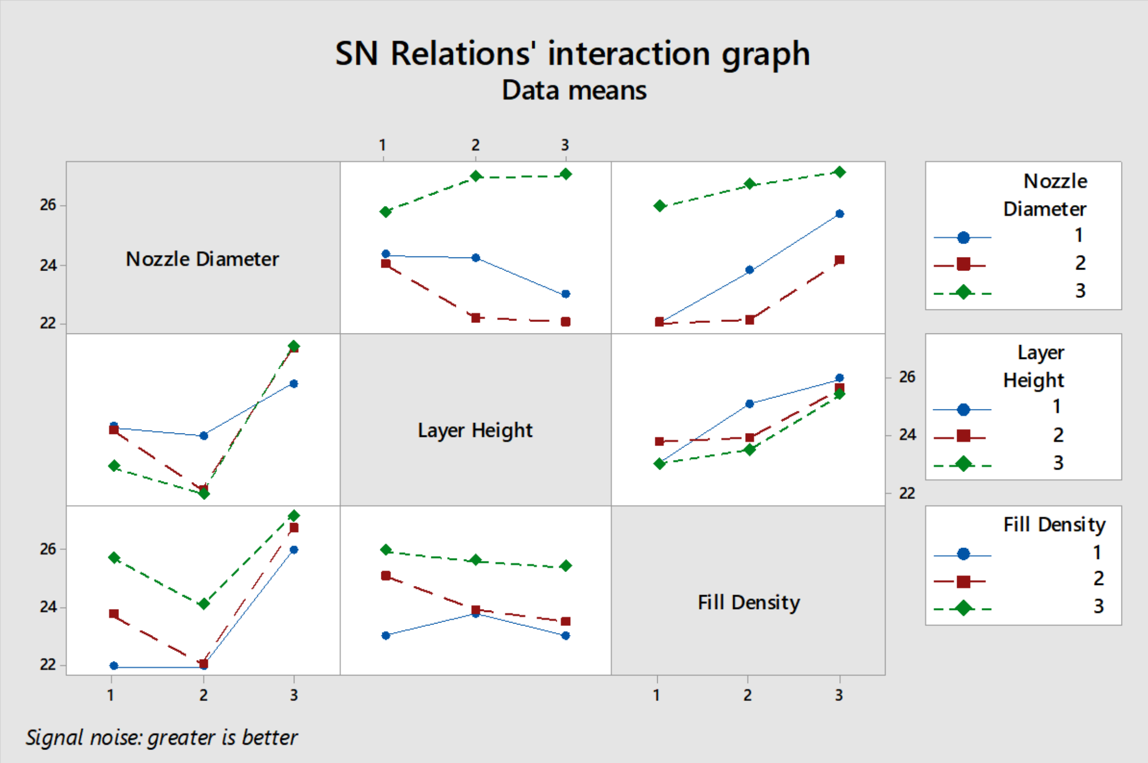

Figure 4.8: Interactions for SN Relations between manufacturing parameters regarding the 0,2% Offset Yield Strength out-parameter

Variance's Analysis for SN Relations Interactions	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,201
Nozzle Diameter vs Fill Density	0,45
Layer Height vs Fill Density	0,665

Table 4.10: P-values of the SN Relations between the manufacturing parameters regarding the 0,2% Offset Yield Strength out-parameter

If there were any doubt on the existence of a robust interaction between parameters from looking at the graph 5.8, the 5.10 table shows the p-values and denies any possible robust interaction. It is important to reiterate that even if there may seem to be an interaction between factors, it doesn't always mean that it is robust or even real. It could be cause by the noise.

It can be said that there is not a single robust interaction between the parameters regarding the 0,2% Offset Yield Strength.

4.3. Ultimate Tensile Strength

It is important to note the difference between the Tensile Strength and the Yield Strength (studied in the previous section before carrying on. The Tensile Strength describes the maximum resistance that a material has to offer before breaking while the Yield Strength describes the maximum resistance that a material has to offer before deforming plastically.

In the table 5.11 it can be seen the results obtained from the traction tests regarding this out-parameter.

Ultimate Tensile Strength σmax (MPa)						
Name	**1**	**2**	**3**	**Mean Value**	**Standard Deviation**	**Error**
ABS-0,3-0,1-25-25-Z0-TRAC	12,44466	12,11687	12,35469	**12,30540551**	**0,169357018**	**0,420706**
ABS-0,3-0,1-50-40-Z45-TRAC	15,15997	16,00168	15,12135	**15,4276708**	**0,497485469**	**1,235822**
ABS-0,3-0,1-75-60-X90-TRAC	23,69787	23,16847	23,74655	**23,53762622**	**0,320627818**	**0,796484**
ABS-0,3-0,2-25-40-Z45-TRAC	13,60108	13,39838	13,69994	**13,56646677**	**0,153727472**	**0,38188**
ABS-0,3-0,2-50-60-X90-TRAC	17,73101	18,10086	17,62384	**17,8185725**	**0,25027488**	**0,621717**
ABS-0,3-0,2-75-25-Z0-TRAC	18,46511	18,62684	18,66663	**18,58619431**	**0,106734213**	**0,265142**
ABS-0,3-0,3-25-60-X90-TRAC	11,95075	11,80107	12,00878	**11,92020136**	**0,107174896**	**0,266237**
ABS-0,3-0,3-50-25-Z0-TRAC	14,66922	14,35884	14,89912	**14,64239623**	**0,271136719**	**0,673541**
ABS-0,3-0,3-75-40-Z45-TRAC	17,55394	17,661	17,70001	**17,63831688**	**0,075633865**	**0,187885**
ABS-0,4-0,1-25-40-X90-TRAC	16,63472	16,40004	16,51121	**16,51532485**	**0,117397308**	**0,291631**
ABS-0,4-0,1-50-60-Z0-TRAC	15,15186	15,22546	15,0004	**15,12590812**	**0,114753345**	**0,285063**
ABS-0,4-0,1-75-25-Z45-TRAC	16,54857	16,75433	16,41109	**16,57132961**	**0,172751187**	**0,429138**
ABS-0,4-0,2-25-60-Z0-TRAC	11,52845	11,40012	11,25442	**11,39433171**	**0,137106954**	**0,340593**
ABS-0,4-0,2-50-25-Z45-TRAC	11,79561	11,92354	11,51236	**11,74383824**	**0,210425729**	**0,522726**
ABS-0,4-0,2-75-40-X90-TRAC	18,6196	18,41	18,53235	**18,52065115**	**0,105287275**	**0,261548**
ABS-0,4-0,3-25-25-Z45-TRAC	11,97722	11,71354	11,62354	**11,77143484**	**0,183806012**	**0,456599**
ABS-0,4-0,3-50-40-X90-TRAC	13,03	13,22244	12,84544	**13,03262434**	**0,188513043**	**0,468292**
ABS-0,4-0,3-75-60-Z0-TRAC	15,68621	15,32354	15,24449	**15,41807934**	**0,235546032**	**0,585129**
ABS-0,6-0,1-25-60-Z45-TRAC	14,65321	14,51255	14,68684	**14,6175323**	**0,092461044**	**0,229686**
ABS-0,6-0,1-50-25-X90-TRAC	25,90486	25,76811	25,96871	**25,88056044**	**0,10248421**	**0,254585**

ABS-0,6-0,1-75-40-Z0-TRAC	21,21451	21,00024	21,29997	**21,17157541**	**0,15440698**	**0,383568**
ABS-0,6-0,2-25-25-X90-TRAC	26,12897	25,97354	26,337	**26,14650206**	**0,182360486**	**0,453009**
ABS-0,6-0,2-50-40-Z0-TRAC	20,53215	20,30265	20,80067	**20,54515633**	**0,249260202**	**0,619197**
ABS-0,6-0,2-75-60-Z45-TRAC	22,20085	21,992	21,97806	**22,0569703**	**0,124794803**	**0,310007**
ABS-0,6-0,3-25-40-Z0-TRAC	22,10019	21,95188	22,02234	**22,02480337**	**0,074183878**	**0,184283**
ABS-0,6-0,3-50-60-Z45-TRAC	20,1463	19,9987	20,29541	**20,14680201**	**0,14835646**	**0,368538**
ABS-0,6-0,3-75-25-X90-TRAC	26,99008	26,9788	26,82368	**26,93085583**	**0,092984203**	**0,230986**

Table 4.11: Mean values of the out-parameters of the Ultimate Strength for each of the configurations of the Taguchi's orthogonal arrangement

4.3.1. Main effects for means

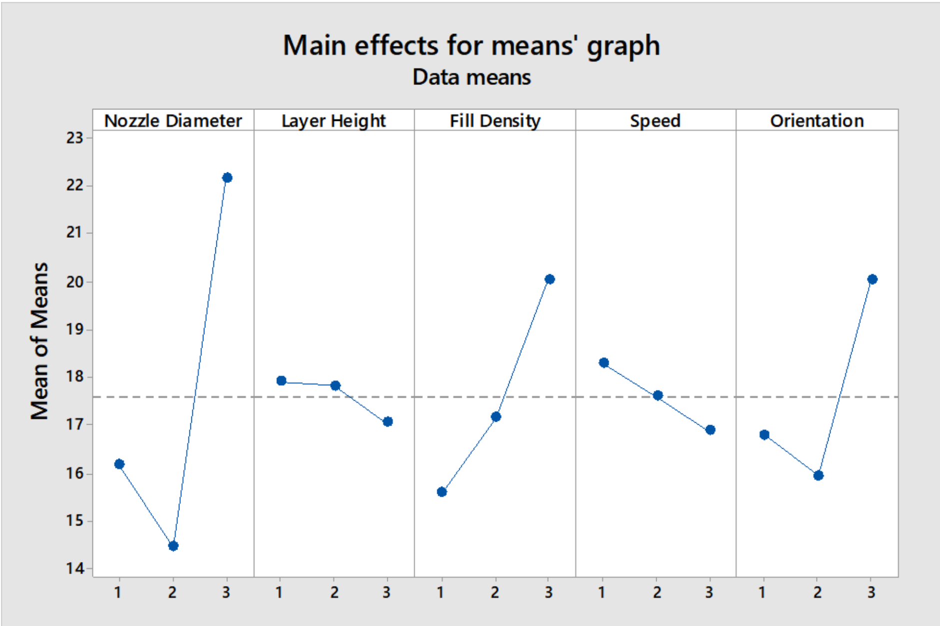

Figure 5.9: Main effects of the manufacturing parameters over the mean values of the Ultimate Tensile Strength

As shown in the figure 5.9 again, the Nozzle Diameter seems to be following the same structure as in the previous sections, it goes down in its second level and it rises drastically when using the 0,6mm nozzle. The Orientation follows the same pattern again but in a lower scale.

The Fill Density once again grows as the levels go up, as expected when filling the specimen with more material in each level. The more internal structure filaments and supports, the higher the resistance of the material.

Finally, the mean of the Ultimate Tensile Strength decreases as the speed grows and the layer height rises.

Variance Analysis for Means					
Source			**p-value**		
Nozzle Diameter			0,03		
Layer Height			0,646		
Fill Density			0,022		
Speed			0,419		
Orientation			0,026		
Response table for Means					
Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	16,16	17,91	15,58	18,29	16,8
2	14,45	17,82	17,15	17,6	15,95
3	22,17	17,06	20,05	16,89	20,03
Delta	7,71	0,85	4,46	1,39	4,08
Rank	1	5	2	4	3

Table 4.12: Level of importance and p-values of the different out-parameters related to the Ultimate Tensile Strength mean value

As seen in the table 5.12, the Nozzle Diameter, Fill Density and Orientation are once again statistically significant because they are inside the 5% significance level (their p-value is inferior than 0,05).

For this particular case, the best arrangement of the parameters and their levels would be. A level three Nozzle Diameter (0,06mm), a level three Fill Density (75%) and a level three Orientation (X90). This arrangement would make a specimen which mean value for the Ultimate Tensile Strength would be the higher possible given the parameters we are working with. For the other no relevant parameters we could choose any of the levels keeping in mind that we could make the par cheaper or make it look better.

4.3.2. Interaction for the Means

As we can see in the graph 5.10, the few cases in which the lines cross each other it happens with a little pendent or angle between them. This suggests that there is not a real interaction between the main factors of manufacturing.

It is confirmed in the 5.13 table afterwards and because of the high p-values values (all of them much higher than 0,05) that there is not any significant interaction between any of the three main factors of the study.

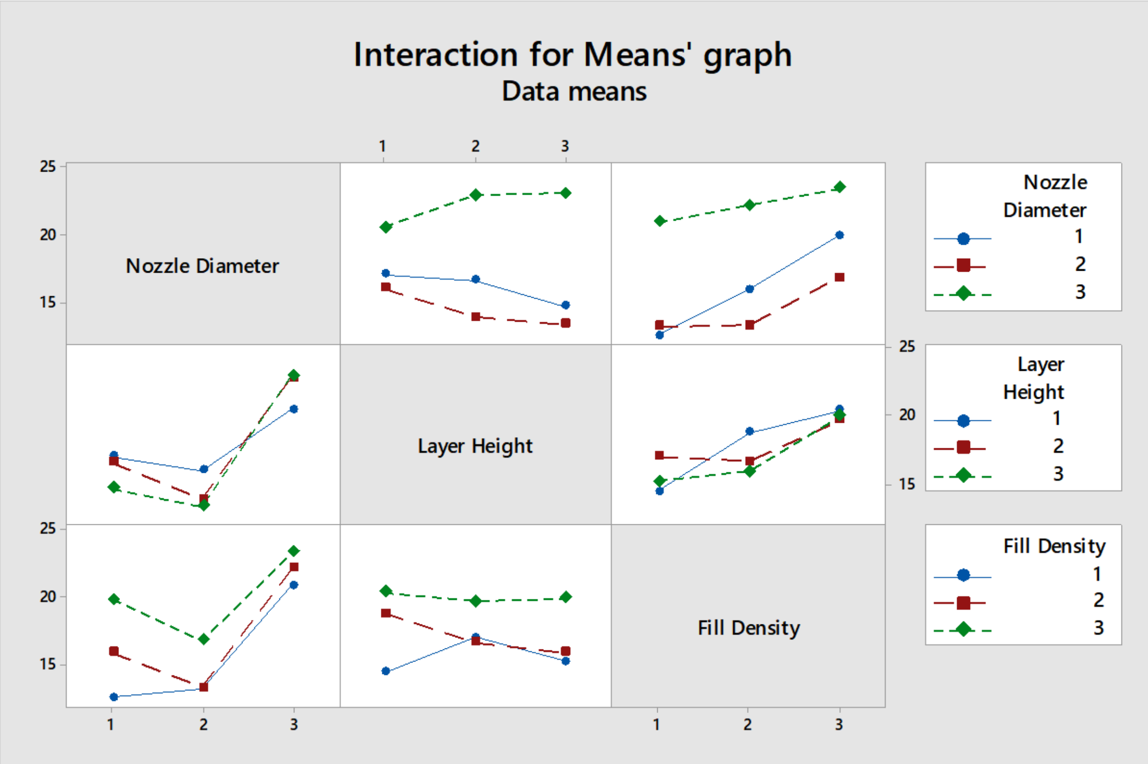

Figure 4.10: Interaction between parameters and relevance on the mean result of the Ultimate Tensile Strength

Interaction for Mean's variance analysis	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,286
Nozzle Diameter vs Fill Density	0,369
Layer Height vs Fill Density	0,41

Table 4.13: P-value of the interactions between manufacturing parameters

4.3.3. Main effects for SN Relations

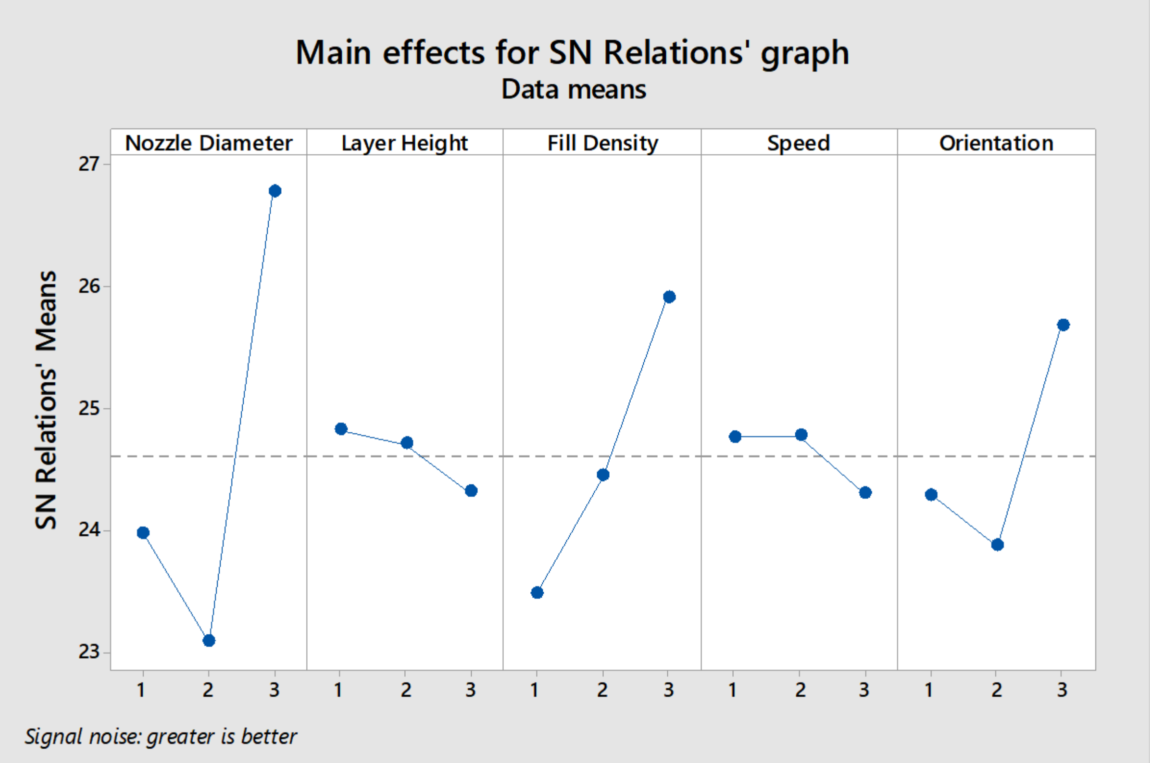

Figure 4.11: Main effects of the manufacturing parameters for the SN Relations over the Ultimate Tensile Strength mean value

Variance Analysis for SN relations					
Source			p-value		
Nozzle Diameter			0,003		
Layer Height			0,58		
Fill Density			0,018		
Speed			0,578		
Orientation			0,042		
SN relations response's table					
Level	Nozzle Diameter	Layer Height	Fill Density	Speed	Orientation
1	23,98	24,82	23,49	24,77	24,29
2	23,08	24,71	24,44	24,78	23,87

3	26,79	24,31	25,92	24,3	25,69
Delta	3,71	0,51	2,43	0,47	1,82
Rank	1	4	2	5	3

Table 4.14: P-values of the SN relations for the manufacturing parameters regarding the Ultimate Tensile Strength out-parameter

As it can be seen in the 5.11 figure, and then confirmed in the 5.14 table, the only three robust parameters are once again the Nozzle Diameter, the Fill Density and the Orientation in this order. Their p-value is inferior to the one of the 5% significance level (0,05). The other two factors seem to be oscillating around the mean value which makes them irrelevant when deciding which level of the robust parameters to choose when manufacturing the parts.

4.3.4. Interaction for SN Relations

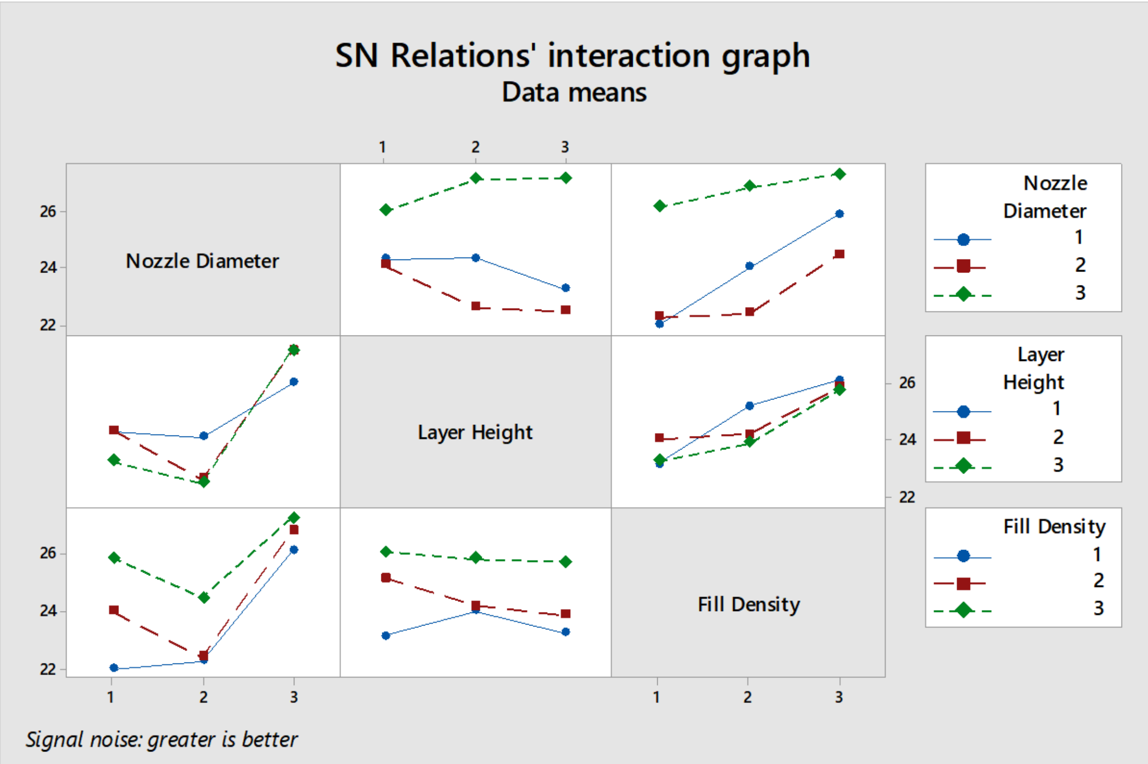

Figure 4.12: Interactions for SN Relations between manufacturing parameters regarding the Ultimate Tensile Strength out-parameter

Just looking at the graph 5.12 it seems that there could be interactions between the Nozzle Diameter and the Layer Height and maybe even between the Layer Height and the Fill Density. But the ANOVA analysis on the 5.15 table confirms that the p-values are in fact too high to be relevant or even exist and thus they must be part of the noise. Once again there is no showing of any robust interaction between factors.

Variance's Analysis for SN Relations Interactions	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,255
Nozzle Diameter vs Fill Density	0,3
Layer Height vs Fill Density	0,615

Table 4.15: P-values of the SN Relations between the manufacturing parameters regarding the Ultimate Tensile Strength out-parameter

4.4. Maximum Elongation

The maximum elongation references the relation between the initial and final length of the part or the variation of its length during the initial application of the traction force until it breaks. It's the capability of the material to resist shape changes without critical damage happening.

The following table 5.16. contains the mean values of the Maximum Elongation out-parameter for each of the 27 configuration and its 3 specimens.

Maximum Elongation emax (%)						
Name	**1**	**2**	**3**	**Mean Value**	**Standard Deviation**	**Error**
ABS-0,3-0,1-25-25-Z0-TRAC	0,785066	0,532185	0,852354	**0,723201673**	**0,168812184**	**0,419353**
ABS-0,3-0,1-50-40-Z45-TRAC	1,0264	0,922454	0,813544	**0,920799238**	**0,106437709**	**0,264406**
ABS-0,3-0,1-75-60-X90-TRAC	0,781596	0,916587	0,600154	**0,766112409**	**0,158783948**	**0,394441**
ABS-0,3-0,2-25-40-Z45-TRAC	1,29317	1,569877	1,301869	**1,388305206**	**0,157305791**	**0,390769**
ABS-0,3-0,2-50-60-X90-TRAC	0,693504	0,454387	0,626874	**0,591588298**	**0,123401699**	**0,306547**
ABS-0,3-0,2-75-25-Z0-TRAC	1,54807	1,601539	1,813547	**1,654385202**	**0,140406746**	**0,34879**
ABS-0,3-0,3-25-60-X90-TRAC	1,844468	1,501384	1,999169	**1,781673526**	**0,254764223**	**0,632869**
ABS-0,3-0,3-50-25-Z0-TRAC	2,643344	2,301569	2,513874	**2,486262193**	**0,172552559**	**0,428644**
ABS-0,3-0,3-75-40-Z45-TRAC	1,36015	1,001645	1,263873	**1,208556114**	**0,185543755**	**0,460916**
ABS-0,4-0,1-25-40-X90-TRAC	1,242766	1,500187	1,333832	**1,358928136**	**0,130532588**	**0,324261**
ABS-0,4-0,1-50-60-Z0-TRAC	1,156722	0,899469	0,999387	**1,018526022**	**0,129690119**	**0,322168**
ABS-0,4-0,1-75-25-Z45-TRAC	1,285846	1,000354	1,501354	**1,262518258**	**0,251313325**	**0,624297**

ABS-0,4-0,2-25-60-Z0-TRAC	1,982592	1,608644	1,813844	**1,801693019**	**0,187270093**	**0,465205**
ABS-0,4-0,2-50-25-Z45-TRAC	1,765746	1,303554	1,989925	**1,686408557**	**0,349995821**	**0,869438**
ABS-0,4-0,2-75-40-X90-TRAC	1,594622	1,001868	1,455235	**1,350575106**	**0,30992695**	**0,769901**
ABS-0,4-0,3-25-25-Z45-TRAC	1,603982	1,320685	1,800154	**1,574940077**	**0,241050142**	**0,598802**
ABS-0,4-0,3-50-40-X90-TRAC	1,060248	0,813874	0,998798	**0,957640036**	**0,128240372**	**0,318567**
ABS-0,4-0,3-75-60-Z0-TRAC	1,70227	1,412287	2,002868	**1,705808393**	**0,295306153**	**0,733581**
ABS-0,6-0,1-25-60-Z45-TRAC	1,15632	1,102868	0,895475	**1,05155436**	**0,137785369**	**0,342278**
ABS-0,6-0,1-50-25-X90-TRAC	1,28617	1,463584	1,501374	**1,417042507**	**0,114903149**	**0,285435**
ABS-0,6-0,1-75-40-Z0-TRAC	1,31572	1,023687	1,121687	**1,153698095**	**0,148624871**	**0,369205**
ABS-0,6-0,2-25-25-X90-TRAC	1,39621	0,999992	1,100087	**1,165429522**	**0,206032725**	**0,511814**
ABS-0,6-0,2-50-40-Z0-TRAC	1,80024	1,520685	2,100685	**1,8072031**	**0,290062693**	**0,720556**
ABS-0,6-0,2-75-60-Z45-TRAC	1,16621	0,792385	1,100684	**1,019759657**	**0,199619507**	**0,495882**
ABS-0,6-0,3-25-40-Z0-TRAC	1,65123	1,323875	1,600644	**1,52524951**	**0,176220329**	**0,437756**
ABS-0,6-0,3-50-60-Z45-TRAC	1,25679	0,994688	1,623547	**1,29167483**	**0,315877647**	**0,784684**
ABS-0,6-0,3-75-25-X90-TRAC	1,34991	1,011216	1,201658	**1,187594785**	**0,169784132**	**0,421767**

Table 4.16: Mean values of the out-parameters of the Maximum Elongation for each of the configurations of the Taguchi's orthogonal arrangement

4.4.1. Main effects for means

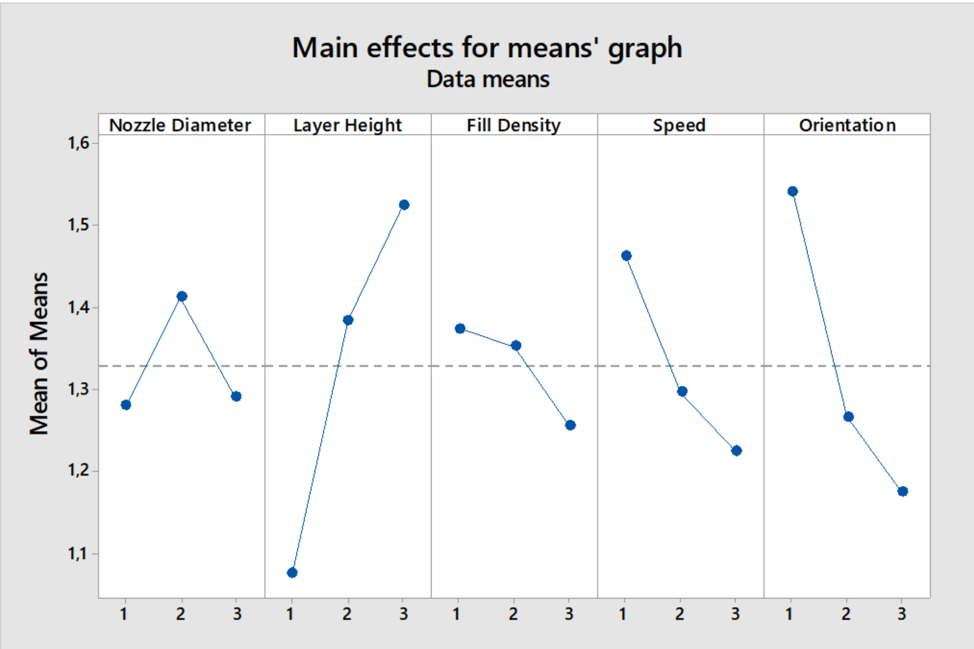

Figure 4.13: Main effects of the manufacturing parameters over the mean values of the Maximum Elongation

Based on the 5.13 graph, the parameter that seems to have a bigger impact on raising the mean value of the Maximum Elongation out-parameter is the Layer Height. It shows a great raise when changing from the first to the second level and once again from changing from the second to the third level.

On the other hand, the Orientation parameter, the Speed parameter and the Fill Density parameter (in a lower degree) show signs of being significant when raising its levels. In the case of the speed it means that when faster the Maximum Elongation parameter goes down and in the case of the Orientation the Z0 position seems to be the one that makes the elongation parameter higher. In the case of the Fill Density it could be that filling more the specimen has a negative effect on the Maximum Elongation, making the material break faster.

The Nozzle Diameter doesn't seem to have a relevant effect on this out-parameter because it goes up and down around the mean value.

Variance Analysis for Means					
Source		**p-value**			
Nozzle Diameter		0,827			
Layer Height		0,257			
Fill Density		0,87			
Speed		0,62			
Orientation		0,36			
Response table for Means					
Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	1,28	1,075	1,375	1,462	1,542
2	1,413	1,385	1,353	1,297	1,267
3	1,291	1,524	1,257	1,225	1,175
Delta	0,133	0,45	0,118	0,237	0,367
Rank	4	1	5	3	2

Table 4.17: Level of importance and p-values of the different out-parameters related to the Ultimate Maximum Elongation mean value

But even if the graph seems to show which parameters are or a are not significant in the mean value of the Maximum Elongation out-parameter, the p-values and the significance level will always tell if they really are.

It can be seen in the 5.17 table that none of the parameters are statistically relevant when trying to maximize the mean value of the out-parameter Maximum Elongation. All of their p-values are greater than 0,05

4.4.2. Interaction for the Means

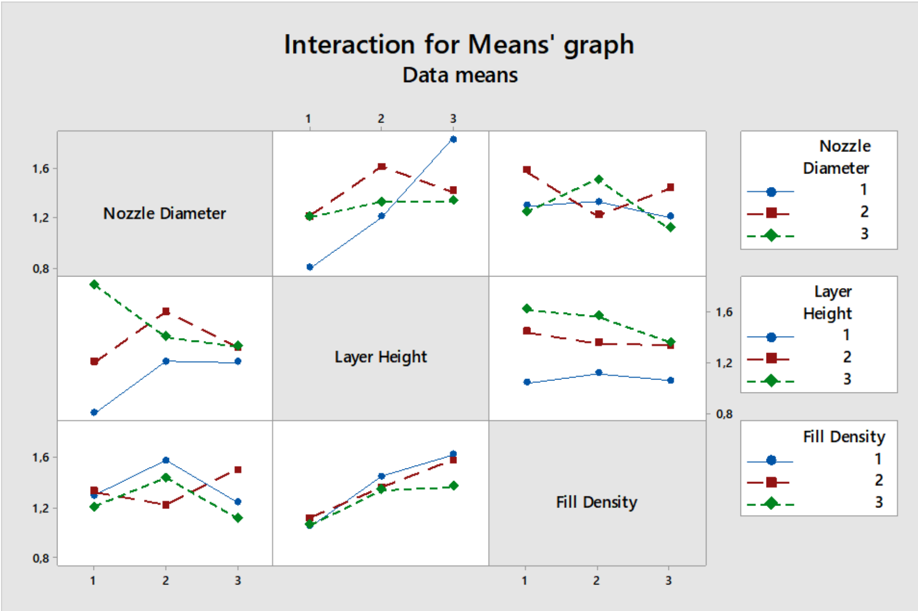

Figure 4.14: Interaction between parameters and relevance on the mean result of the Maximum Elongation

Interaction for Mean's variance analysis	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,53
Nozzle Diameter vs Fill Density	0,811
Layer Height vs Fill Density	0,986

Table 4.18: P-value of the interactions between manufacturing parameters

As it can be intuited in the 5.14 figure and then confirmed in the 5.18 table there is not any significant relation between parameters that can affect the mean value of the Maximum Elongation out-parameter. The only possible interaction that could seem possible would be the one between the Nozzle Diameter and the Layer Height but when looking at its p-value it can be seen that it is 10 times bigger than 0,05.

This makes sense if we think in the previous section. Not any of the parameters were relevant when changing the mean value of the Maximum Elongation, so it is only normal that they don't have any reliable influence in the mean value when related to one another.

4.4.3. Main effects for SN Relations

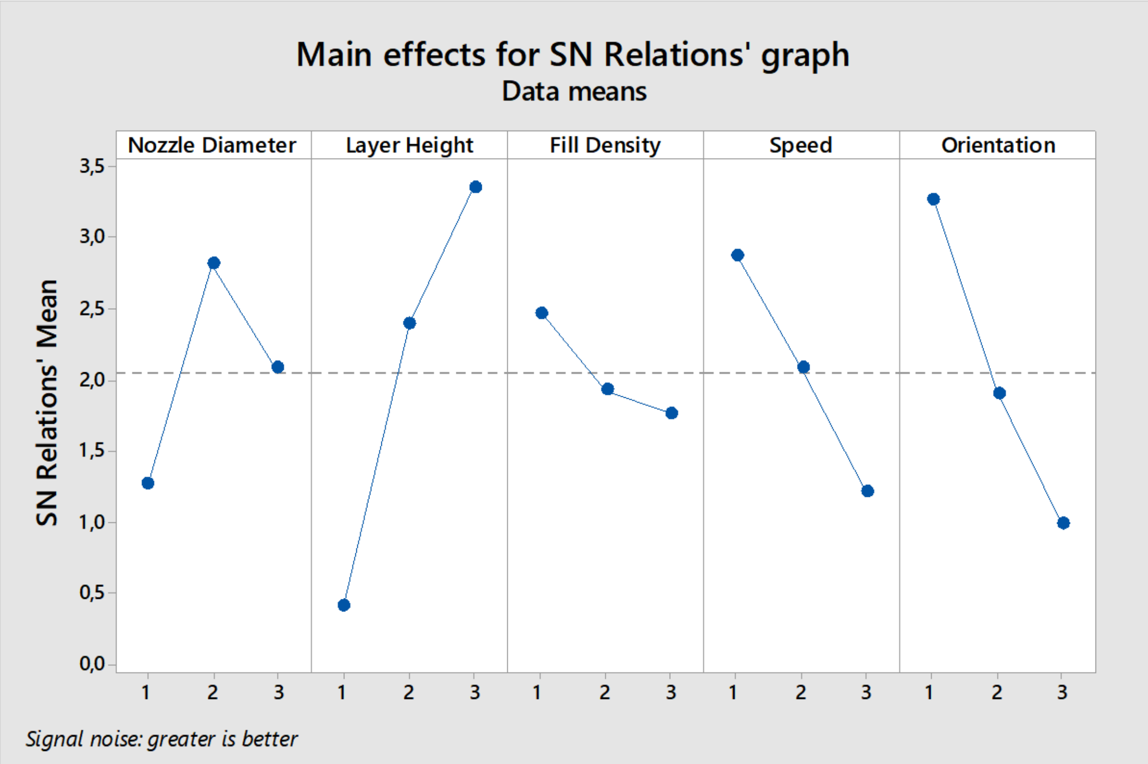

Figure 4.15: Main effects of the manufacturing parameters for the SN Relations over the Maximum Elongation mean value

According to the 5.15 figure, the properties that seem to be more robust are the Layer Height that raises the mean when making it bigger, and the Orientation, which have the contrary effect, the Z0 orientation makes the mean higher and the X90 makes it lower.

The Fill Density and the speed also have a down effect when going up their levels (more fill density and speed) but don't seem to have enough of an impact.

Finally, the Nozzle Diameter goes up and down around the mean looking like it is not a robust parameter in any case.

Variance Analysis for SN relations	
Source	**p-value**
Nozzle Diameter	0,663

Layer Height			0,29		
Fill Density			0,904		
Speed			0,627		
Orientation			0,443		
SN relations response's table					
Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	1,2656	0,4121	2,4675	2,87	3,2699
2	2,8133	2,3962	1,9276	2,081	1,9019
3	2,081	3,3516	1,7648	1,209	0,988
Delta	1,5477	2,9395	0,7027	1,661	2,2819
Rank	4	1	5	3	2

Table 4.19: P-values of the SN relations for the manufacturing parameters regarding the Maximum Elongation out-parameter

As predicted using the graph, the table 5.19 confirms that the Layer Height and the Orientation parameters seem to be the most robust ones, but it is not statistically relevant because their p-values are much greater than the 0,05 value. They are out of the 5% confidence level.

None of the parameters studied should be considered robust and relevant when trying to maximize the out-parameter Maximum Elongation.

4.4.4. Interaction for SN Relations

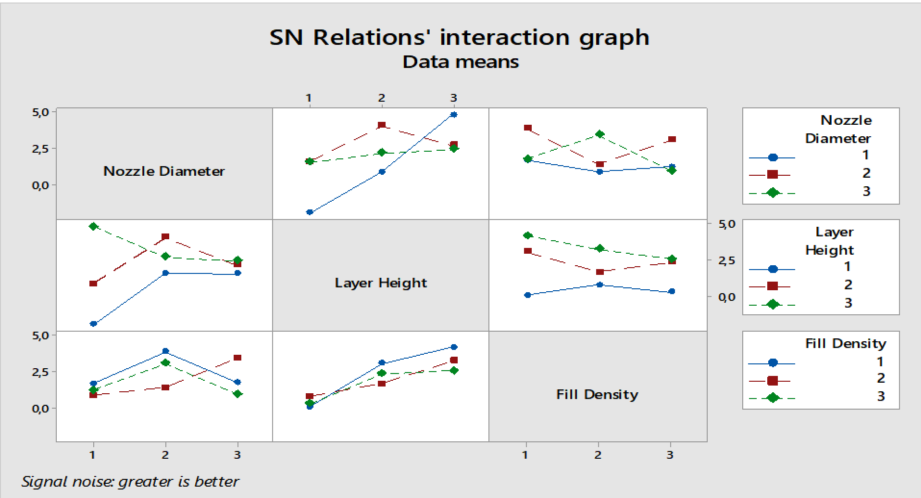

Figure 4.16: Interactions for SN Relations between manufacturing parameters regarding the Maximum Elongation out-parameter

Variance's Analysis for SN Relations Interactions	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,561
Nozzle Diameter vs Fill Density	0,818
Layer Height vs Fill Density	0,972

Table 4.20: P-values of the SN Relations between the manufacturing parameters regarding the Maximum Elongation out-parameter

In the previous section it was confirmed that none of the parameters were to be considered robust. It is only normal that the interaction between non robust parameters turned out to be not robust. It can be confirmed looking at the p-values of the table 5.20 that not a single interaction between the three main manufacturing parameters is to be considered statistically robust.

4.5. Resilience Module

The Resilience Module references the deformation energy per volume unit that it is requires to deform the material until reaching its elastic limit. In the following table the mean value of the Resilience Module obtained during the tests of the specimens can be found.

The table 5.21 shows the results obtained in the traction tests:

Resilience Module MR (Mpa)						
Name	**1**	**2**	**3**	**Mean Value**	**Standard Deviation**	**Error**
ABS-0,3-0,1-25-25-Z0-TRAC	0,053641	0,031568	0,04999	**0,045066283**	**0,011831164**	**0,02939**
ABS-0,3-0,1-50-40-Z45-TRAC	0,06572	0,040544	0,071187	**0,059150028**	**0,016343878**	**0,0406**
ABS-0,3-0,1-75-60-X90-TRAC	0,095861	0,121685	0,085685	**0,101076756**	**0,018558078**	**0,046101**
ABS-0,3-0,2-25-40-Z45-TRAC	0,063227	0,033355	0,041685	**0,046088756**	**0,01541545**	**0,038294**
ABS-0,3-0,2-50-60-X90-TRAC	0,069038	0,095135	0,022	**0,062057652**	**0,037063745**	**0,092071**
ABS-0,3-0,2-75-25-Z0-TRAC	0,0819	0,111054	0,100007	**0,097653665**	**0,014719033**	**0,036564**
ABS-0,3-0,3-25-60-X90-TRAC	0,04974	0,022269	0,059942	**0,043983374**	**0,019484952**	**0,048403**
ABS-0,3-0,3-50-25-Z0-TRAC	0,057033	0,032688	0,049917	**0,04654595**	**0,012517998**	**0,031096**
ABS-0,3-0,3-75-40-Z45-TRAC	0,081418	0,081268	0,099855	**0,08751363**	**0,01068793**	**0,02655**
ABS-0,4-0,1-25-40-X90-TRAC	0,069321	0,055168	0,071688	**0,065392381**	**0,008932906**	**0,022191**
ABS-0,4-0,1-50-60-Z0-TRAC	0,069592	0,035512	0,05992	**0,055008227**	**0,017562936**	**0,043629**

ABS-0,4-0,1-75-25-Z45-TRAC	0,071384	0,042269	0,061157	**0,058269864**	**0,014770741**	**0,036693**
ABS-0,4-0,2-25-60-Z0-TRAC	0,046684	0,019999	0,04	**0,035560844**	**0,013885338**	**0,034493**
ABS-0,4-0,2-50-25-Z45-TRAC	0,046771	0,048499	0,046788	**0,047352593**	**0,000992632**	**0,002466**
ABS-0,4-0,2-75-40-X90-TRAC	0,078553	0,085688	0,062298	**0,075513011**	**0,011987233**	**0,029778**
ABS-0,4-0,3-25-25-Z45-TRAC	0,047557	0,032648	0,05	**0,043401757**	**0,009392389**	**0,023332**
ABS-0,4-0,3-50-40-X90-TRAC	0,052194	0,033336	0,059995	**0,04850882**	**0,013706342**	**0,034048**
ABS-0,4-0,3-75-60-Z0-TRAC	0,061674	0,068899	0,052999	**0,061190373**	**0,007961049**	**0,019776**
ABS-0,6-0,1-25-60-Z45-TRAC	0,060945	0,038168	0,07993	**0,059681013**	**0,020909675**	**0,051943**
ABS-0,6-0,1-50-25-X90-TRAC	0,120004	0,099975	0,188649	**0,136209285**	**0,046504911**	**0,115525**
ABS-0,6-0,1-75-40-Z0-TRAC	0,098754	0,079877	0,089876	**0,089502328**	**0,009444422**	**0,023461**
ABS-0,6-0,2-25-25-X90-TRAC	0,130316	0,15988	0,148235	**0,146143632**	**0,014892409**	**0,036995**
ABS-0,6-0,2-50-40-Z0-TRAC	0,090033	0,062544	0,079969	**0,077515109**	**0,013907801**	**0,034549**
ABS-0,6-0,2-75-60-Z45-TRAC	0,0989	0,111686	0,094677	**0,101754218**	**0,008856942**	**0,022002**
ABS-0,6-0,3-25-40-Z0-TRAC	0,098876	0,113514	0,084649	**0,09901272**	**0,014433098**	**0,035854**
ABS-0,6-0,3-50-60-Z45-TRAC	0,095476	0,119877	0,089969	**0,101773845**	**0,015917408**	**0,039541**
ABS-0,6-0,3-75-25-X90-TRAC	0,131026	0,171658	0,1	**0,134227803**	**0,035935858**	**0,08927**

Table 4.21: Mean values of the out-parameters of the Resilience Module for each of the configurations of the Taguchi's orthogonal arrangement

4.5.1. Main effects for means

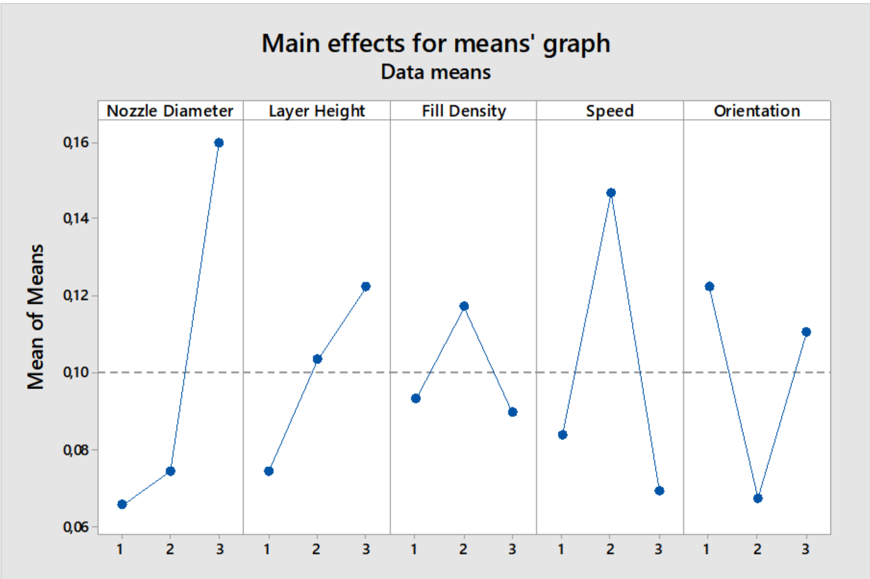

Figure 4.17: Main effects of the manufacturing parameters over the mean values of the Resilience Module

The 5.17 graph shows that the main parameter that seems relevant when affecting the mean value of the Resilience Module is the Nozzle Diameter. The bigger the nozzle, the higher the mean value of the Resilience Module. The Layer Height also shows hints of raising the mean value the bigger it is, but in a much lower scale than the Nozzle Diameter.

The Speed and the Fill Density are at their maximum on their second level (45mm/s and 50%). Finally, it seems like the preferred Orientations are Z0 and X90.

Variance Analysis for Means	
Source	**p-value**
Nozzle Diameter	0,057
Layer Height	0,354
Fill Density	0,628
Speed	0,111
Orientation	0,254

Response table for Means					
Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	0,06546	0,07437	0,09314	0,084	0,12232
2	0,07446	0,10328	0,11711	0,147	0,06722
3	0,15996	0,12223	0,08963	0,069	0,11034
Delta	0,0945	0,04786	0,02748	0,078	0,0551
Rank	1	4	5	2	3

Table 4.22: Level of importance and p-values of the different out-parameters related to the Resilience Module mean value

The 5.22 table shows that effectively, the Nozzle Diameter is the most influential parameter but it should be not considered statistically relevant when trying to make the Resilience Module higher, even though its p-value (0,057) is so close of the limit value (0,05) to be considered relevant. The other manufacturing parameters should be not considered relevant; their p-values are far away from the 5% confidence level limit.

4.5.2. Interaction for the Means

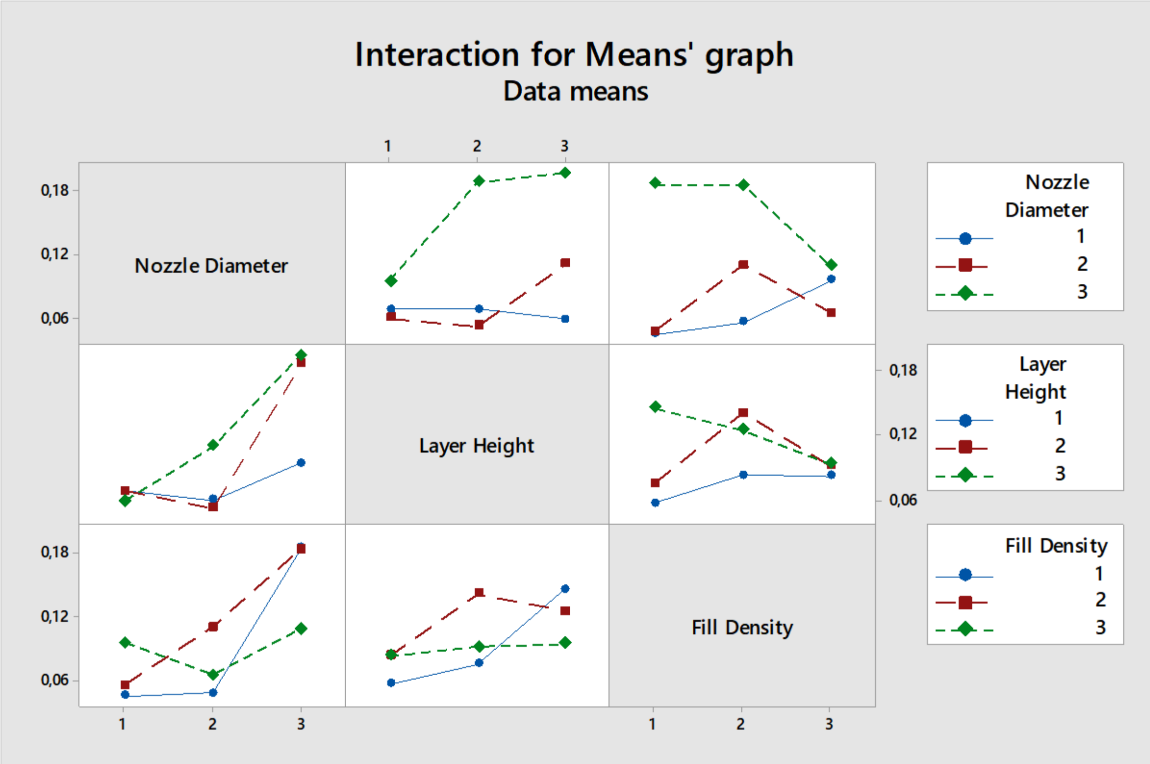

Figure 4.18: Interaction between parameters and relevance on the mean result of the Resilience Module

Interaction for Mean's variance analysis	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,513
Nozzle Diameter vs Fill Density	0,434
Layer Height vs Fill Density	0,699

Table 4.23: P-value of the interactions between manufacturing parameters

As seen in the 5.18 graph and based on the previous sections it doesn't seem that any of the interactions have any real influence on the mean value of the Resilience Module. It seems logical taking into account that not a single parameter was to be considered relevant on its own.

It is confirmed in the table 5.23 that there is not any existent interaction between parameters that is relevant when trying to design a par taking into account its Resilience Module.

4.5.3. Main effects for SN Relations

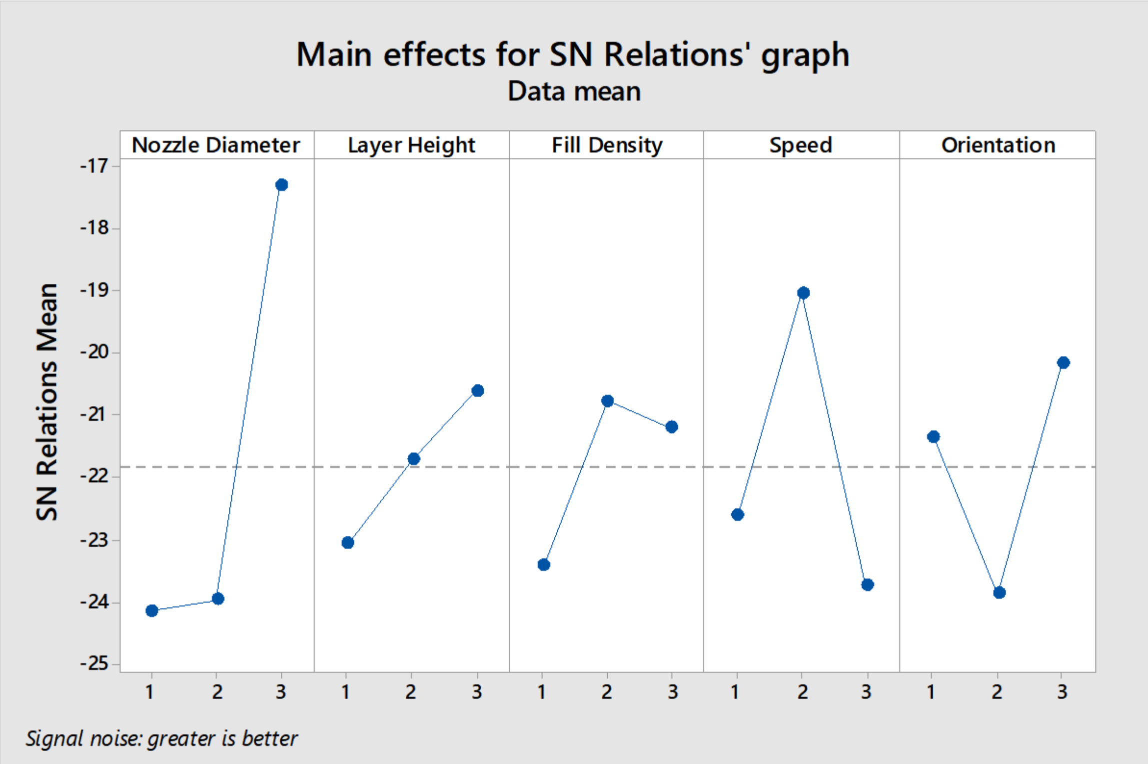

Figure 4.19: Main effects of the manufacturing parameters for the SN Relations over the Resilience Module mean value

Variance Analysis for SN relations	
Source	**p-value**
Nozzle Diameter	0,012
Layer Height	0,313
Fill Density	0,236
Speed	0,058
Orientation	0,121

SN relations response's table					
Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	-24,16	-23,08	-23,44	-22,63	-21,35
2	-23,98	-21,72	-20,78	-19,04	-23,9

3	-17,29	-20,62	-21,21	-23,76	-20,18
Delta	6,87	2,46	2,66	4,71	3,72
Rank	1	5	4	2	3

Table 4.24: P-values of the SN relations for the manufacturing parameters regarding the Resilience Module out-parameter

As it can be checked in the table 5.24 and with the support of the 5.19 figure it is shown how the only manufacturing parameter to be considered robust regarding the Resilience Module is the Nozzle Diameter. To make the Resilience Module more invariable in front of the deformation the Nozzle Diameter should be set to its level three (0,6mm). The others parameters could be set into any other configuration, taking into account monetary or aspect reasons of the final part.

4.5.4. Interaction for SN Relations

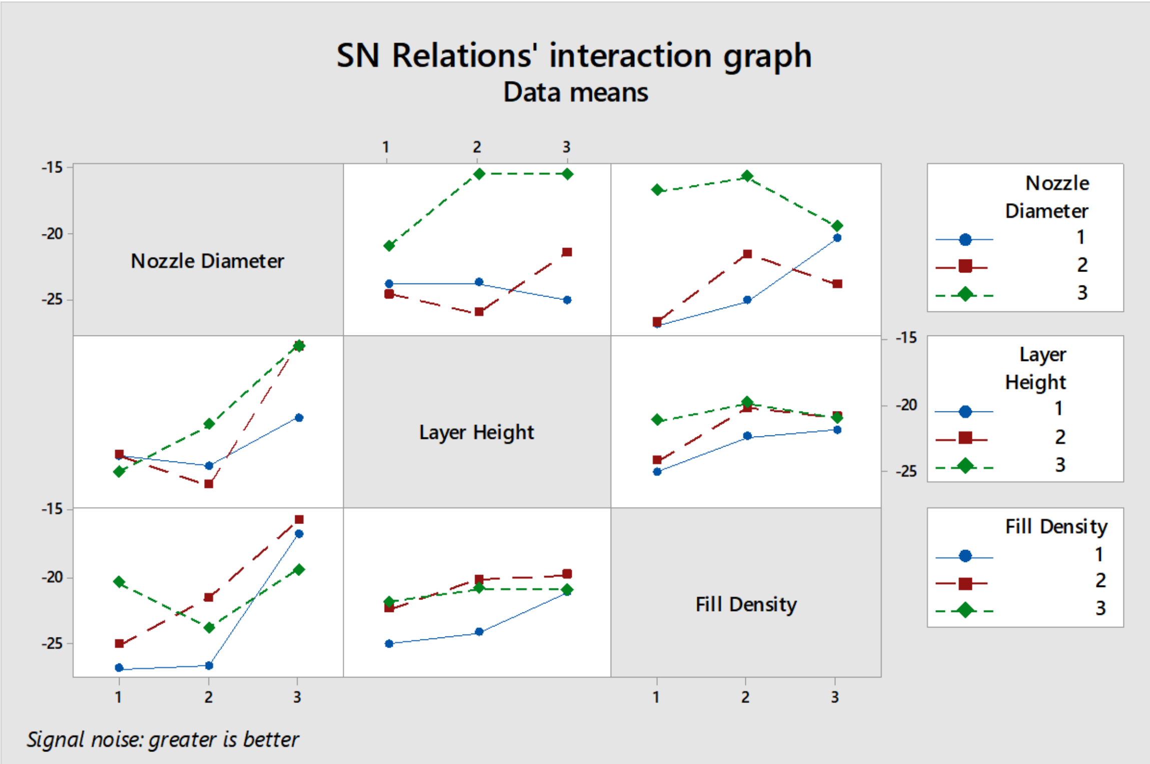

Figure 4.20: Interactions for SN Relations between manufacturing parameters regarding the Resilience Module out-parameter

Variance's Analysis for SN Relations Interactions	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,269
Nozzle Diameter vs Fill Density	0,182

Layer Height vs Fill Density	0,854

Table 4.25: P-values of the SN Relations between the manufacturing parameters regarding the Resilience Module out-parameter

In the 5.20 graph it can be observed how the majority of the lines are practically parallel between one another or in the cases they are not, the inclination between them is not high enough to make us suspicious of a possible robust interaction between factors.

As confirmed in the 5.25 table, the p-values are much greater than the frontier 0,05 value set to be considered to be inside of the confidence level. It can be assured that there are not any robust interactions that will assure no variation in front of the out-parameter resilience Module.

4.6. Resilience Module

The Resilience Module references the quantity of energy that the material is capable of absorbing from the point it starts its plastic deformation until its breaking point.

In the following table (Table 5.26) the mean values of the Resilience Module for each of the configuration can be found.

Tenacity Module MT (Mpa)						
Name	1	2	3	Mean Value	Standard Deviation	Error
ABS-0,3-0,1-25-25-Z0-TRAC	0,05838241 2	0,08535431 4	0,06006877 6	**0,06793516 7**	**0,015108969**	**0,03753276**
ABS-0,3-0,1-50-40-Z45-TRAC	0,08860721 9	0,07468457 4	0,05898756 5	**0,07409311 9**	**0,014818682**	**0,03681164 7**
ABS-0,3-0,1-75-60-X90-TRAC	0,09221979 3	0,07168435 4	0,12064321 7	**0,09484912 1**	**0,024585109**	**0,06107279 6**
ABS-0,3-0,2-25-40-Z45-TRAC	0,09442231 4	0,06216874 7	0,08956846 5	**0,08205317 5**	**0,017390596**	**0,04320063 6**
ABS-0,3-0,2-50-60-X90-TRAC	0,07354423 9	0,10167684 4	0,81676546 9	**0,33066218 4**	**0,42121273**	**1,04635042 7**
ABS-0,3-0,2-75-25-Z0-TRAC	0,17702272 5	0,13268435 4	0,22354684 3	**0,17775130 7**	**0,045435626**	**0,11286835 2**
ABS-0,3-0,3-25-60-X90-TRAC	0,18340823	0,15648784 4	0,17996843 5	**0,17328817**	**0,014650811**	**0,03639463 2**
ABS-0,3-0,3-50-25-Z0-TRAC	0,29384313 8	0,32138763 4	0,25546876 8	**0,29023318**	**0,033107372**	**0,08224327 1**

ABS-0,3-0,3-75-40-Z45-TRAC	0,187859589	0,182384435	0,160138434	**0,176794153**	**0,014681759**	**0,036471512**
ABS-0,4-0,1-25-40-X90-TRAC	0,155769013	0,141351348	0,135432139	**0,144184167**	**0,010460199**	**0,025984575**
ABS-0,4-0,1-50-60-Z0-TRAC	0,100351231	0,051323454	0,092398741	**0,081357809**	**0,026312685**	**0,065364333**
ABS-0,4-0,1-75-25-Z45-TRAC	0,165636017	0,198768432	0,170065784	**0,178156744**	**0,017987133**	**0,044682517**
ABS-0,4-0,2-25-60-Z0-TRAC	0,155864362	0,101346844	0,142585385	**0,13326553**	**0,02842859**	**0,070620532**
ABS-0,4-0,2-50-25-Z45-TRAC	0,141775086	0,100016481	0,166666639	**0,136152735**	**0,03367891**	**0,083663051**
ABS-0,4-0,2-75-40-X90-TRAC	0,196630543	0,245315354	0,189913844	**0,210619914**	**0,030234231**	**0,075105993**
ABS-0,4-0,3-25-25-Z45-TRAC	0,123826606	0,092387135	0,111946544	**0,109386762**	**0,015875278**	**0,039436377**
ABS-0,4-0,3-50-40-X90-TRAC	0,10042592	0,075138438	0,150006461	**0,108523607**	**0,038085228**	**0,094608952**
ABS-0,4-0,3-75-60-Z0-TRAC	0,165692917	0,133238434	0,159943848	**0,1529584**	**0,01731822**	**0,043020842**
ABS-0,6-0,1-25-60-Z45-TRAC	0,065413746	0,042115314	0,055164435	**0,054231165**	**0,011677221**	**0,029007824**
ABS-0,6-0,1-50-25-X90-TRAC	0,112369124	0,152121358	0,120354385	**0,128281622**	**0,021028335**	**0,052237279**
ABS-0,6-0,1-75-40-Z0-TRAC	0,151391279	0,192687654	0,161684654	**0,168587862**	**0,021496241**	**0,053399623**
ABS-0,6-0,2-25-25-X90-TRAC	0,139547567	0,100564684	0,12009682	**0,12006969**	**0,019491456**	**0,04841946**
ABS-0,6-0,2-50-40-Z0-TRAC	0,187914227	0,22268265	0,20068168	**0,203759519**	**0,017587372**	**0,043689453**
ABS-0,6-0,2-75-60-Z45-TRAC	0,135444751	0,098106817	0,122684651	**0,118745406**	**0,018978108**	**0,047144234**
ABS-0,6-0,3-25-40-Z0-TRAC	0,214578654	0,250061652	0,181065161	**0,215235155**	**0,03450293**	**0,08571003**
ABS-0,6-0,3-50-60-Z45-TRAC	0,140036549	0,101684087	0,166616016	**0,136112217**	**0,032643363**	**0,081090609**
ABS-0,6-0,3-75-25-X90-TRAC	0,184650118	0,162684654	0,152268458	**0,16653441**	**0,016530531**	**0,041064115**

Table 4.26: Mean values of the out-parameters of the Tenacity Module for each of the configurations of the Taguchi's orthogonal arrangement

4.6.1. Main effects for means

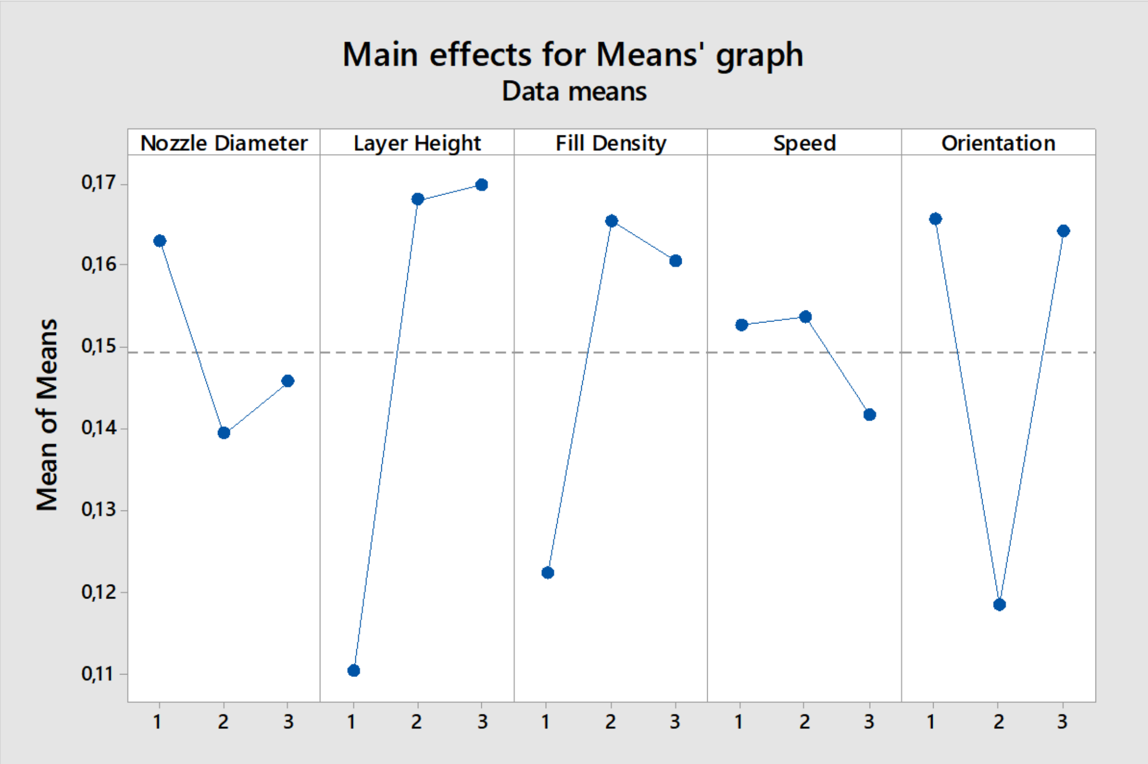

Figure 4.21: Main effects of the manufacturing parameters over the mean values of the Tenacity Module

The manufacturing parameters regarding the Tenacity Module seem to have a very particular effect on it compared how the parameters affected the previous studied out-parameters.

The three that seem having the most influence regarding the Tenacity Module according to the 5.21 graph are: The Layer Height, the Fill Density and the Orientation. The Nozzle Diameter and the Speed seem to be around the mean throughout their level changes.

It seems that when using a bigger Layer Height, the mean of the Tenacity Module raises. This change is the most noticeable between the first and the second level of the Layer Height. The Fill Density also has a great increase between its first and second level.

The Orientation on the other hand seems to make the mean raise when using the Z0 and X90 configurations which seems only normal if we think that the Z45 configuration doesn't have an intern pattern aligned with the traction force thus not providing as much capability of resistance as the other two configurations.

Variance Analysis for Means	
Source	**p-value**
Nozzle Diameter	0,29
Layer Height	0,017
Fill Density	0,057
Speed	0,636
Orientation	0,038

Response table for Means					
Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	0,1631	0,1102	0,1222	0,153	0,1657
2	0,1394	0,1681	0,1655	0,154	0,1184
3	0,1457	0,1699	0,1606	0,142	0,1641
Delta	0,0237	0,0597	0,0433	0,012	0,0473
Rank	4	1	3	5	2

Table 4.27: Level of importance and p-values of the different out-parameters related to the Tenacity Module mean value

The table 5.27 shows that the analysis made just from the 5.21 graph was correct. The Layer Height and the Orientation are definitely statistically relevant because from the values taken from the ANOVA analysis it can be seen that their values are inside the 5% confidence level. The Fill Density however falls short to be considered relevant when affecting the mean value of the Tenacity Module.

To maximize the Tenacity Module, the best configuration would be a Layer Height a level three Layer Height (0,3mm) and a level 1 Orientation (Z0). The rest of the parameters could be configured to make the part cheaper or better looking.

4.6.2. Interaction for the Means

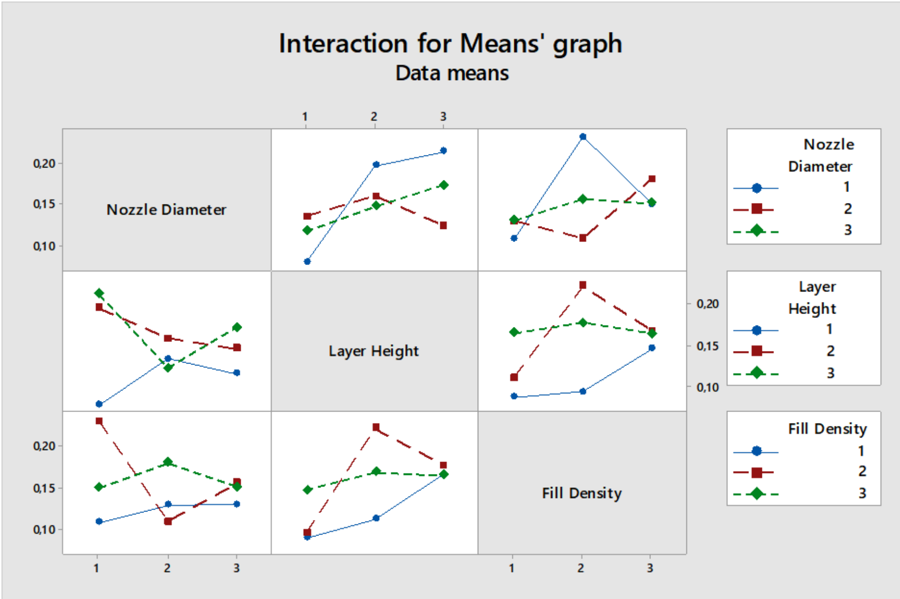

Figure 4.22: Interaction between parameters and relevance on the mean result of the Tenacity Module

Interaction for Mean's variance analysis	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,059
Nozzle Diameter vs Fill Density	0,04
Layer Height vs Fill Density	0,079

Table 4.28: P-value of the interactions between manufacturing parameters

For the first time an out-parameter seems to have its mean influenced by the interaction of two manufacturing parameters. In the graph 5.22 it is clear that there is a big pendent between more than one of the parameters. Perhaps the most noticeable one would be the one between the Nozzle Diameter and the Fill Density.

According to the 5.28 table this interaction exists and it is statistically relevant according to its p-value (0,04). It is correct to say that the interaction between the Nozzle Diameter and the Fill Density can help raise the mean value of the Tenacity Module.

The interaction between the Nozzle Diameter and the Layer Height falls just a bit short from being considered relevant.

4.6.3. Main effects for SN Relations

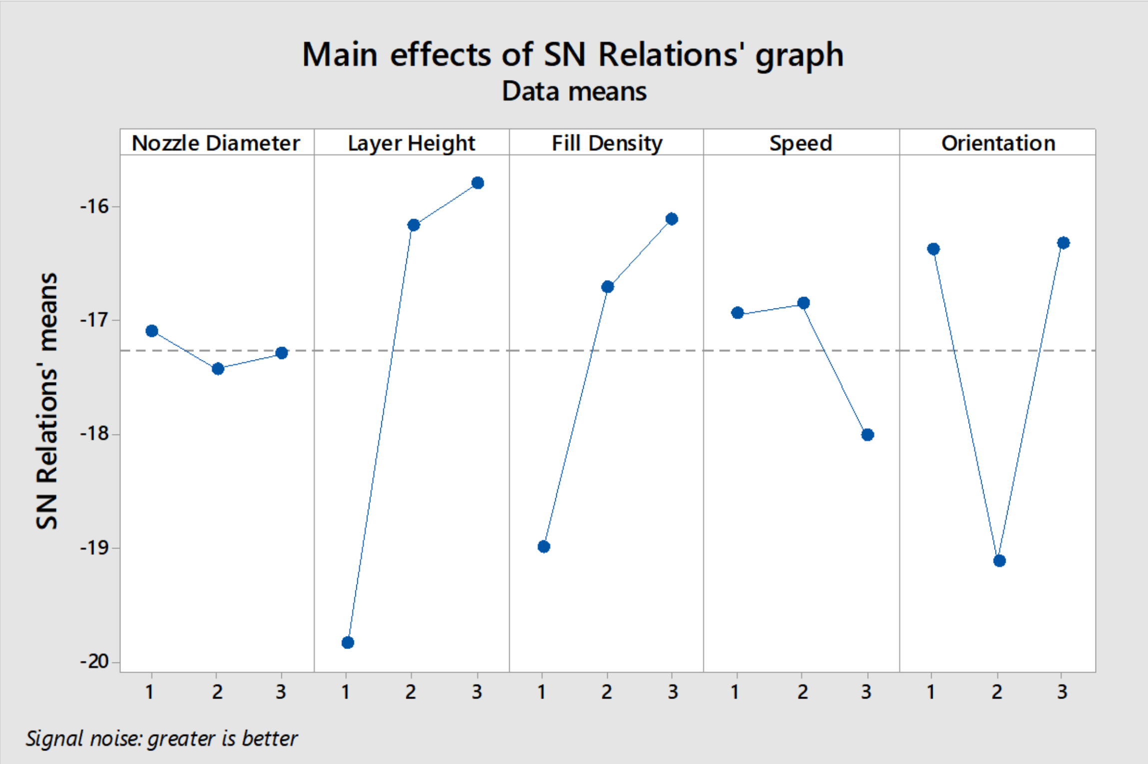

Figure 4.23: Main effects of the manufacturing parameters for the SN Relations over the Tenacity Module mean value

Variance Analysis for SN relations	
Source	**p-value**
Nozzle Diameter	0,919
Layer Height	0,013
Fill Density	0,048
Speed	0,373
Orientation	0,041

SN relations response's table					
Level	**Nozzle Diameter**	**Layer Height**	**Fill Density**	**Speed**	**Orientation**
1	-17,09	-19,85	-18,99	-16,94	-16,37
2	-17,42	-16,16	-16,7	-16,85	-19,12

3	-17,29	-15,79	-16,1	-18,01	-16,31
Delta	0,33	4,06	2,89	1,16	2,81
Rank	5	1	2	4	3

Table 4.29: P-values of the SN relations for the manufacturing parameters regarding the Tenacity Module out-parameter

The Layer Height seems to be the predominant factor and the most robust one when trying to make the out-parameter Tenacity Module inflexible to the noise according to the graph 5.23 and the table 5.29. The Fill Density follows the same path as the Layer Height but in a smaller scale.

The Orientation seems to follow the same path as in the previous section and it looks like it is higher when working with the Z0 and X90 configurations.

The Nozzle Diameter and the Speed move around the mean value and they don't seem like robust parameters.

Once again it has to be checked whether what we thought were robust parameter are in reality robust. The p-values of the Layer Height and the Orientation are in fact inside the 0,05 threshold that limits if a parameter can be considered robust or not.

The Layer Height and Orientation can be considered parameters that are not affected by the noise and thus give us a certainty of results in front of the out-parameter Tenacity Module.

4.6.4. Interaction for SN Relations

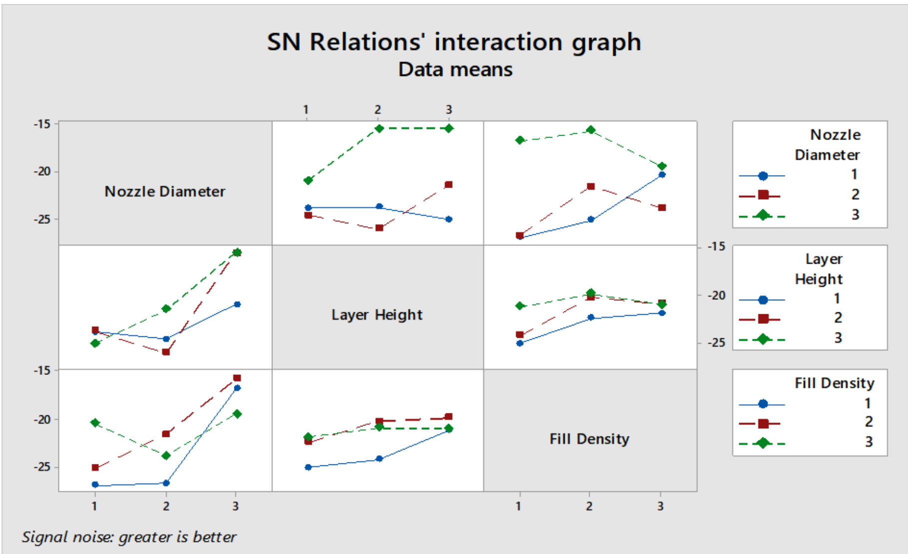

Figure 4.24: Interactions for SN Relations between manufacturing parameters regarding the Tenacity Module out-parameter

Variance's Analysis for SN Relations Interactions	
Source	**p-value**
Nozzle Diameter vs Layer Height	0,066
Nozzle Diameter vs Fill Density	0,084
Layer Height vs Fill Density	0,107

Table 4.30: P-values of the SN Relations between the manufacturing parameters regarding the Tenacity Module out-parameter

Finally regarding the interactions between factors and their effect on the signal to noise relations it seems like there is not any relation worth considered statistically robust. The one that shows the most potential in the graph 5.24 is the Nozzle Diameter and Layer Height one but it's once again discarded the p-values obtained by the ANOVA analysis in the table 5.30. All the p-values from the interactions are far greater than the 0,05 limit.

5. Results discussion

The traction tests done over the 3 specimens that form each of the 27 configurations have allowed obtaining results regarding the traction resistance and the ductility of the ABS material. The values of the out-parameters have varied depending on the configuration of the manufacturing parameters used for each of the 27 arrangements.

This experiment has not only given results on the mechanical properties of the manufactured specimens but also in the role and importance that each of the parameters modified during the printings have had over the final results or final properties of the parts. The study on the parameters is important in order to get the most out of them when fabricating parts using FFF technology. If the influence that the manufacturing parameters have over the final parts is known it will be possible to manufacture parts according to our own needs, desires and benefits.

This section will contain a summary of the studied sections and a cross analysis between the results obtained from the excel sheets and the results obtained from the Minitab software in order to see the why's and how's of the parameters chosen and the final results.

5.1. Traction resistance

The Stress-Strain curve obtained from the traction tests has allowed obtaining the so called out-parameters from the information that it gives.

The graph shows a classical straight rising section at the beginning where the tension grows proportional to the deformation of the part. In this section is where the Young's Module is obtained. Calculations has been made to be able to find the straightest line from this initial part so it is possible to have the less error when obtaining the Young's Module. The Elastic Module (Young's Module) determines how elastic or rigid a part is.

The Elastic Limit is the tension that the material will be able to resist without suffering permanent deformations. To be able to do this, the Elastic Limit has been set to 0.2 %, as it is standard to do so it is more practical to work with and identify. A straight parallel line next to the initial portion of the curve has been created in order to obtain this point (where this line crosses the main graph). The higher its value is,, the more tension the part will be able to sustain without suffering permanent deformations.

The Ultimate Tensile Strength can be found when reaching the maximum point of the curve. This is the place where the material is under more tension. The point of maximum tension.

After obtaining the results from the out-parameters from the excel sheets and after putting them through the Minitab software under the Taguchi's design analysis some common factors that have the capability to better this traction property.

The most important factor and the one that have the biggest influence over the three properties (out-parameters) mentioned before is the Nozzle Diameter. This parameter is followed by the Fill Density and the Orientation in this order. This three are the statistically significant manufacturing parameters that can better the properties of the parts in relation to its traction resistance.

The Nozzle Diameter makes better these tension properties by extruding thicker threads. This makes the most sense when thinking we are working with specimens that are not completely solid. This means that when not being a cohesive part, the specimens have to rely on the inside structure to maintain its unity. The bigger the threads extruded the less possible structural mistakes. More over thicker supports make for better reinforcement than thinner ones due to their capability of accumulating heat and tension. Furthermore, the thinner threads can create residual tension that affects negatively the structural integrity of the part and its capability of sustaining bigger tensions.

The Orientation of the part can also help or harm its properties depending on the direction they are printed. In this case, the two orientations that favor the traction properties are the ones set on the first level (Z0) and the third level (X90). This is because in these cases the specimens are printer following the same direction that the force that they will be under. When the part is printed following the direction of the force it affects positively to its properties. This is the reason that the specimens have a worst performance when printed with a 45-degree pattern. If the specimen was to be printed in a 90 degree pattern it would perform even worse.

The last of the three parameters is perhaps the most obvious one. A part with a higher infill will always be able to sustain more tension than a lower infill part. This is why the higher tensions in this experiment are always found when working with the 75% infill specimens, followed by the 50% infill ones and lastly the worst performing ones, the 25% filled specimens.

Regarding the interactions, the ANOVA analysis has not been able to find any between the three main factors studied. This is curious in the case of the Nozzle Diameter and the Layer Height. All the manufacturers and softwares recommend that the Layer Height should be between a 15 and a 75% of the Nozzle Diameter. If we make the Layer Height too high, the threads will be deposited one on top of the others in a more rounded shape, making the contact between layers worse than if they were having a perfect rectangular contact. On the other hand, if really little Layer Heights were to be used the resolution and quality of the part would be worse, because the parts forming the machine would have to work really slowly needing a precision that not all the machines have.

The reason why this relation has not been detected in the analysis could be because we are in fact inside of the optimal range and thus this interaction doesn't have any effect whatsoever in the performance of the specimens.

The Speed doesn't seem to have any effect on the out-parameters. This could because the printer is capable of printing under these speeds with no major changes in the overall integrity of the part.

If we would have chosen a worst printer, we might have been able to appreciate a negative effect when using higher speeds. The other reason is because we haven't used speeds that apart from each other (30mm/s, 45mm/s and 60mm/s) and we are not able to see significant changes when jumping from one speed to another.

5.2. Ductility

Like in the previous section, we will use the data obtained in the Taguchi analysis and in the excel sheets to study the effects that the manufacturing parameters have this time on the capability of the material to internalize energy. The capability to deform either elastically or plastically without breaking.

In this case, when talking about the Maximum Deformation there's not a single factor that is relevant enough to consider that betters or worsens the Maximum Elongation out-parameter. Looking at the data it is easy to see that this out-parameter doesn't vary much across the 27 configurations which might make the parameters irrelevant.

Regarding the Resilience Module, it happens a curious thing. While the Nozzle Diameter cannot be considered influential enough to change the mean value of this out-parameter, it is considered robust against the noise. This parameter could turn out in fact useful because its p-value is really close to the 0,05 threshold, so it would be wrong to discard it when its considered robust. In any case because of its robustness and because it shows that it makes the Resilience Module higher when using a bigger Nozzle Diameter, it should always be taken into account.

The Tenacity Module shows the first interaction between parameters that affect its mean value. The Nozzle Diameter and the Fill Density combined can make the Tenacity Module have higher value. Moreover, the Layer Height and the Orientation are considered to be capable to make this out-parameter better on their own. An Orientation in favor of the tension applied betters the tenacity, and a greater Layer Height helps do the same. The Fill Density should be taken into consideration taking into account that it is also considered a robust parameter and doesn't vary or add noise to the out-parameter Tenacity Module.

As we have seen the Speed is not a relevant or robust factor through all this out-parameters. This can be, as said before, because the machine used is capable of manufacturing efficiently with all the speeds used and the structural integrity of the part doesn't depend on it. A worst machine could show that the Speed is in fact a relevant factor. This could also be because of the capability of the material (ABS) to deposit its layers on top of the previous ones with ease and that it doesn't need as much time to settle. This are all hypothesis that could be confirmed by making the study with other materials.

6. Conclusions

After taking into account the obtained data from the out-parameters and the data from the Minitab analysis the following conclusions can be extracted:

- The project has aimed to identify which of the manufacturing parameters have a real and bigger influence in the final properties of the printed parts when under traction forces. The Nozzle Diameter, Fill Density and Orientation play the biggest roles in this department.
- The parts manufactured by Fused Filament Fabrication suffer changes in their mechanical properties because the manufacturing parameters directly influence or change their behavior as unit.
- The threads size and its orientation have a big influence over the elastic properties of the material. A material manufactured with threads that align with the forces it is under resist them better. On the other hand, a material made out of threads parallel to the force it is under will handle it worst.
- The infill of the material has a big influence on how rigid the parts are.
- To obtain better traction resistance the following configuration have to be chosen:
    - Nozzle Diameter: 0,6mm
    - Fill Density: 75%
    - Orientation: X90
- Not any of the manufacturing parameters seem to have a relevant effect on the Maximum Elongation of the parts.
- The Nozzle Diameter is a robust parameter to take into account when manufacturing part that should be able to elastically deform. A 0.6 mm Nozzle Diameter offers the best results to better the Resilience Module.
- A higher Layer Height (0.3mm) and a X90 Orientation make for better results of the Tenacity Module.
- The Fill Density parameter is considered robust in front all the noise signals that can affect the Tenacity Module. It should be taken into account when planning on designing parts thinking on their tenacity.
- The Speed doesn't have any impact on either the resistance or ductile properties. This might be because the machine is good enough to handle them or the jumps between speeds haven't been significant enough.
- Knowing the influence that the manufacturing parameters have over the fabricated parts gives us an advantage when manufacturing parts under the influence of traction forces. This means that it will allow us to set the best configuration from each parameter so that the created part works as intended.
- Once the relevant parameters that affect the mechanical properties of a part are known, the ones that doesn't have any effect on the final result can be set to the values that will give the most economic saving.

7. Cost analysis

The following section shows the buys (Table 6.1), equipment used (Table 6.2), cost of the working hours (Table 6.3) and energy consumption (Table 6.4) generated during the duration of this project. Finally, in the table 8.5 the sum of all the costs is calculated to have the final value of the total cost of the project.

Consumable equipment			
Concept	**Quantity**	**Unit Cost (€)**	**Total Cost (€)**
ABS plastic (coil)	3	24.95	74.85
Brass gotend Nozzle 0.3 mm	2	9.68	19.36
Brass gotend Nozzle 0.4 mm	2	9.68	19.36
Brass gotend Nozzle 0.6 mm	2	9.68	19.36
Hobbed Bolt M8 + Nuts	1	7.87	7.87
3DLAC 400ml	1	7.20	7.2
BCNNNozzle Hotend with nozzle 0.4	1	36.30	36.3
Wire extender for Nema 17 with connector	2	3.63	7.26
Pololu DRV8825	1	5.32	5.32
		TOTAL	**196.88**

Table 7.1: Consumable equipment

Non-expandable equipment			
Concept	**Cost (€)**	**Amortization (%)**	**Total (€)**
Computer	1,500.00	10	150
BCN3D+	800	25	32
Solidworks Student Edition	Free software	5	-
Slic3r	Free software	25	-
Netfabb	Free software	10	-

Microsoft Excel 2010	135	25	5.4
Minitab 17	Free software	10	-
		TOTAL	**187.4**

Table 7.2: Non-expandable equipment

Human Resources			
Concept	**Hours**	**€/hour**	**Total (€)**
Documentation	80	8	640
Design of Taguchi Method	7.5	8	60
Parametrization of experiments with Slic3r software	5	8	40
3D printing of the specimens	181.3	8	1450.4
Repairing of 3D printer (1)	21	8	168
Repairing of 3D printer (2)	10	8	80
Repairing of 3D printer (3)	10	8	80
Metrology and weighing of the samples	3.5	8	28
Elaboration of the traction test Protocol	12.5	8	100
Traction Tests	24	8	192
Design of the Excel Spreadsheet	65	8	520
Taguchi's Analysis with Minitab	15	8	120
		TOTAL	**3478.4**

Table 7.3: Human Resources

Manufacturing Costs				
Concept	**Hours**	**Power requirements (kWh)**	**Price of electricity (€/kWh)**	**Total Cost (€)**
Printing hours by the 3D printer BCN3D+	181.3	0.2	0.12522	**4.54**

Table 7.4: Manufacturing Costs

Breakdown of the Project's cost	**Cost (€)**
Consumable equipment	196.88
Non-expandable equipment	187.4
Human Resources	3478.4
Manufacturing Costs	4.54
TOTAL Project's Cost	**3867.22**

Table 7.5: Total cost of the Project

The cost of the project adds up to a total of **3867.22 euros**.

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9. Annex 1: Stress-Strain curves

This annex contains all the curves extracted from the exels sheets result of the traction tests. Each of the 27 figures contain the stress-strain curve of the 3 specimens that form each configuration.

The X axis represents the elasticity (e) in % and the Y axis represents the strain (σ) in MPa. The blue curve represents the first specimen, the orange curve represents the second specimen and the green curve represents the third specimen.

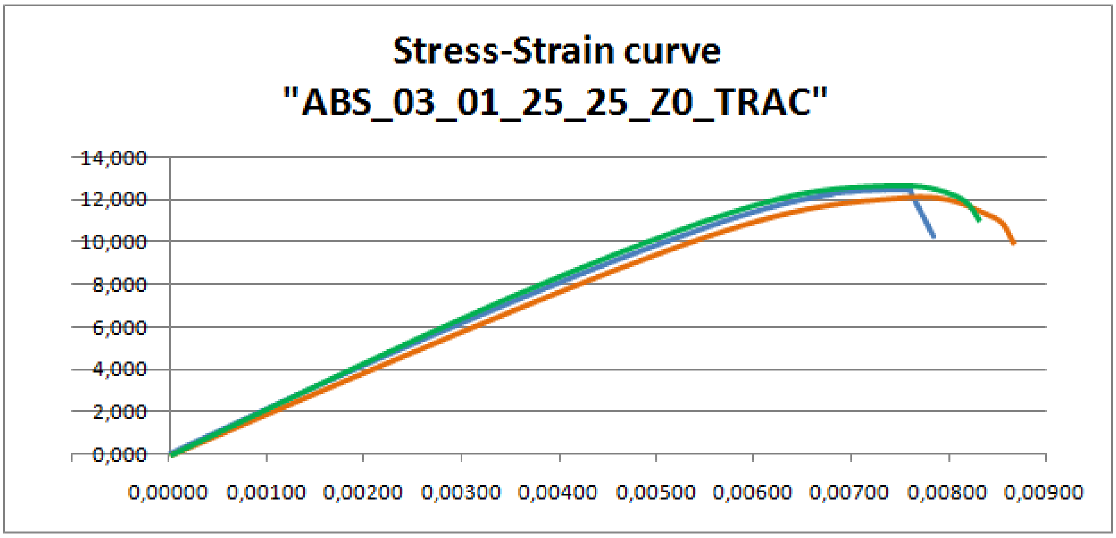

Figure A1.1: Stress-Strain curve "ABS-0,3-0,1-25-25-Z0-TRAC"

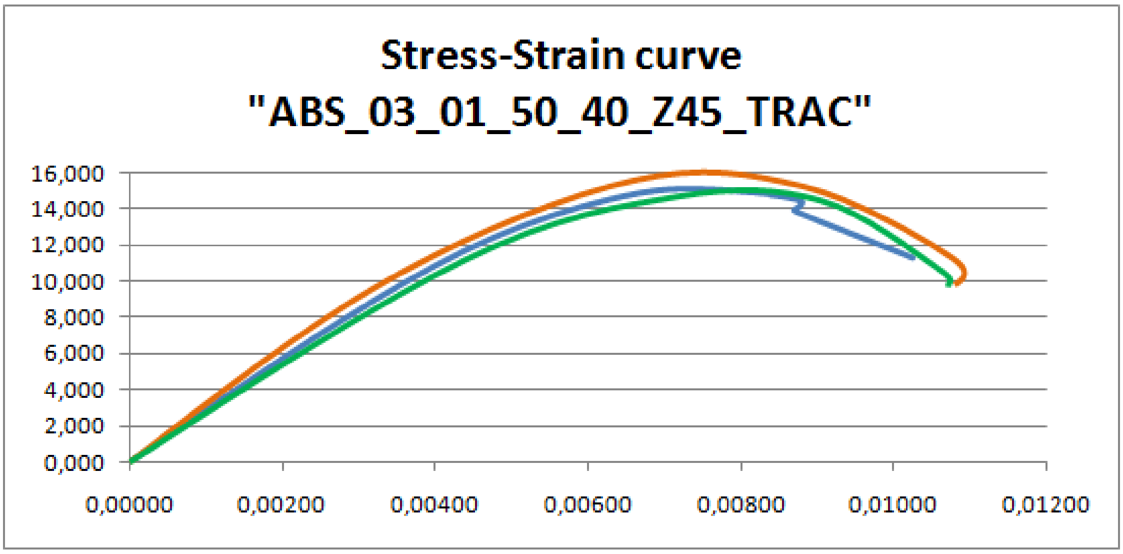

Figure A2.2: Stress-Strain curve "ABS-0,3-0,1-50-40-Z45-TRAC"

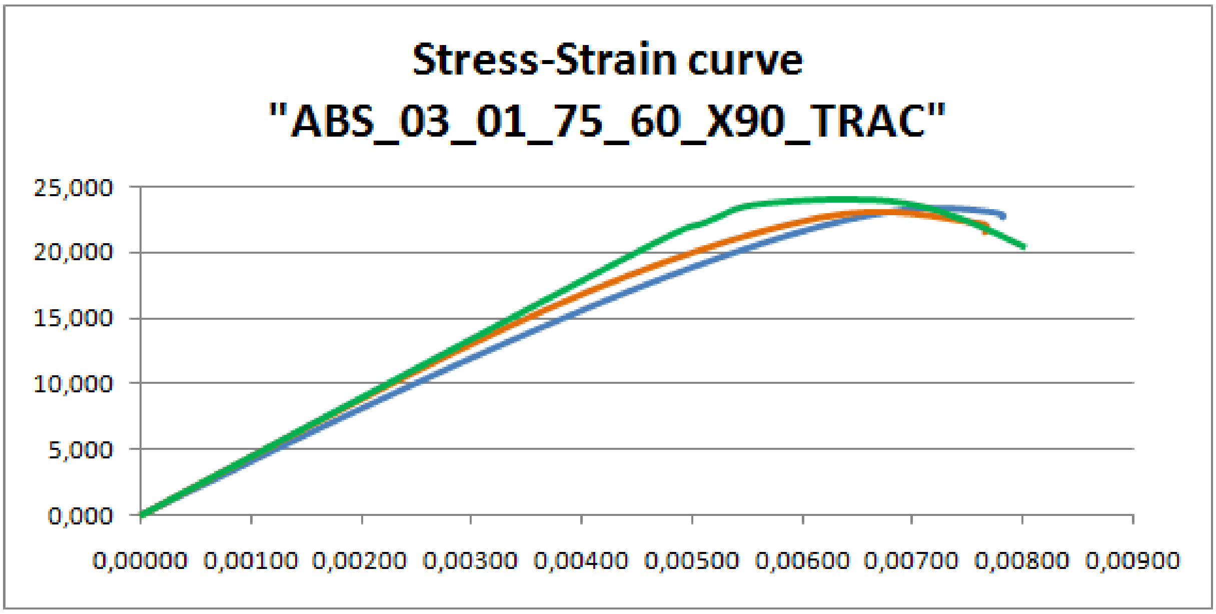

Figure A1.3: Stress-Strain curve "ABS-0,3-0,1-75-60-X90-TRAC"

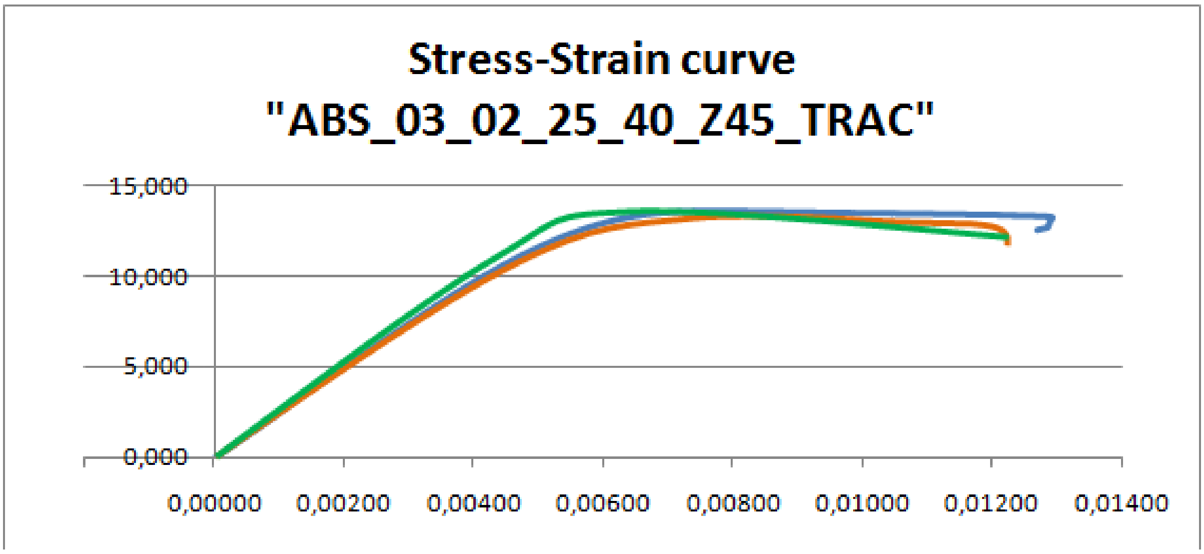

Figure A1.4: Stress-Strain curve "ABS-0,3-0,2-25-40-Z45-TRAC"

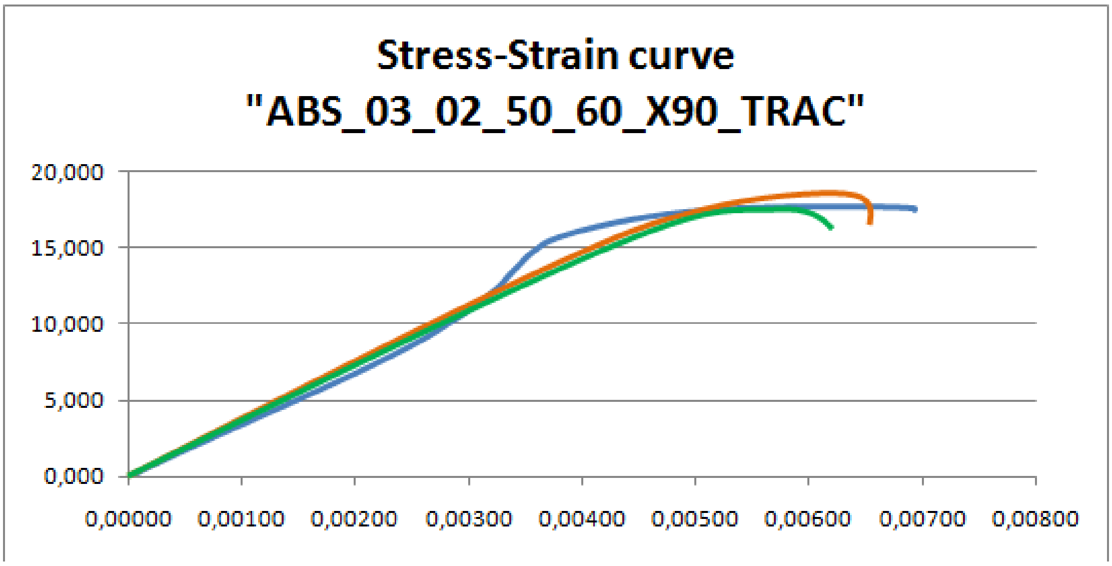

Figure A1.5: Stress-Strain curve "ABS-0,3-0,2-50-60-X90-TRAC"

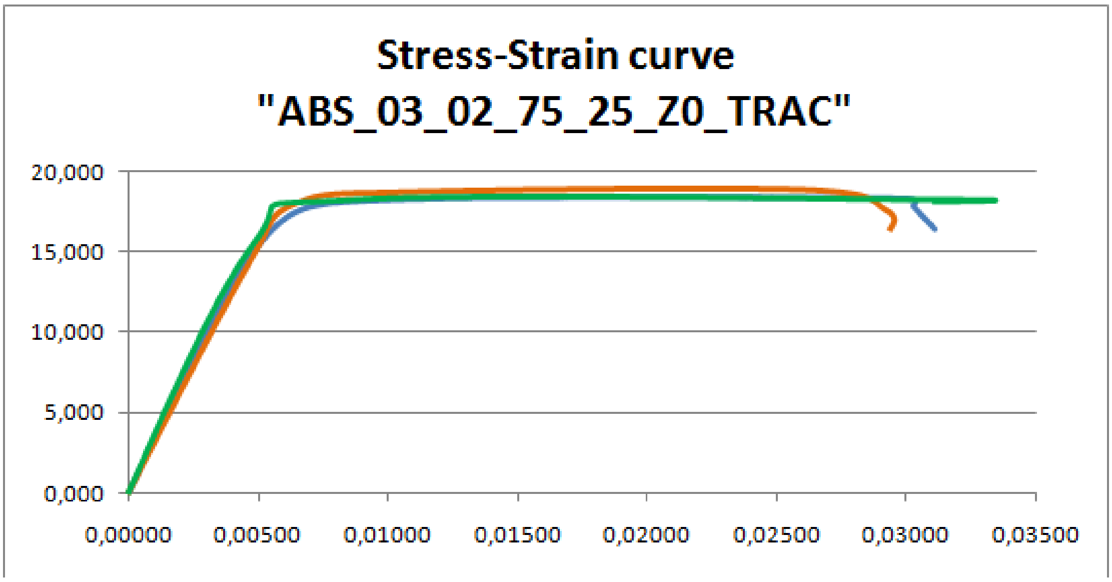

Figure A1.6: Stress-Strain curve "ABS-0,3-0,2-75-25-Z0-TRAC"

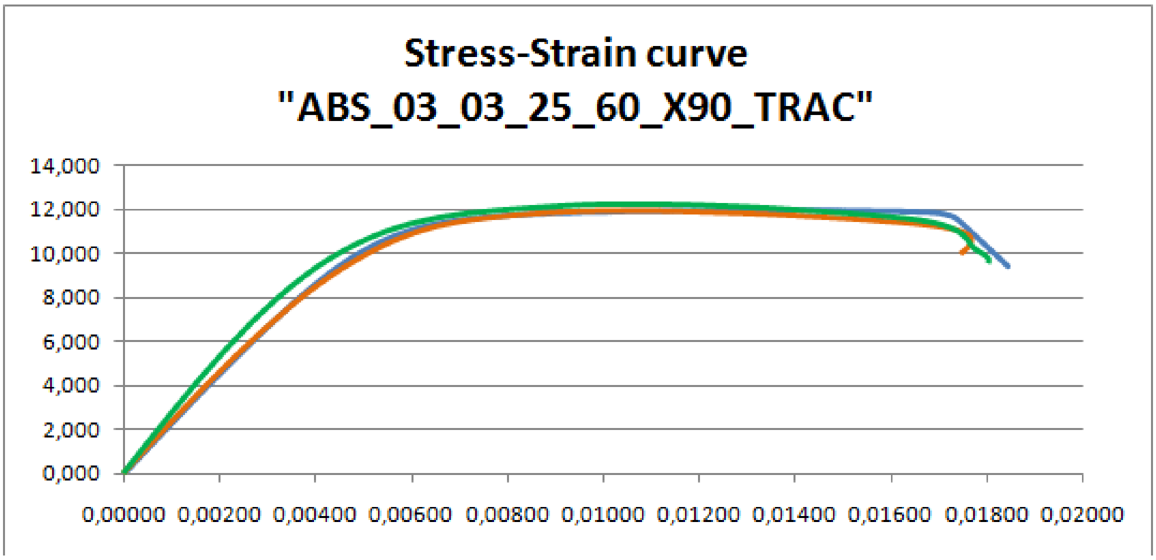

Figure A1.7: Stress-Strain curve "ABS-0,3-0,3-25-60-X90-TRAC"

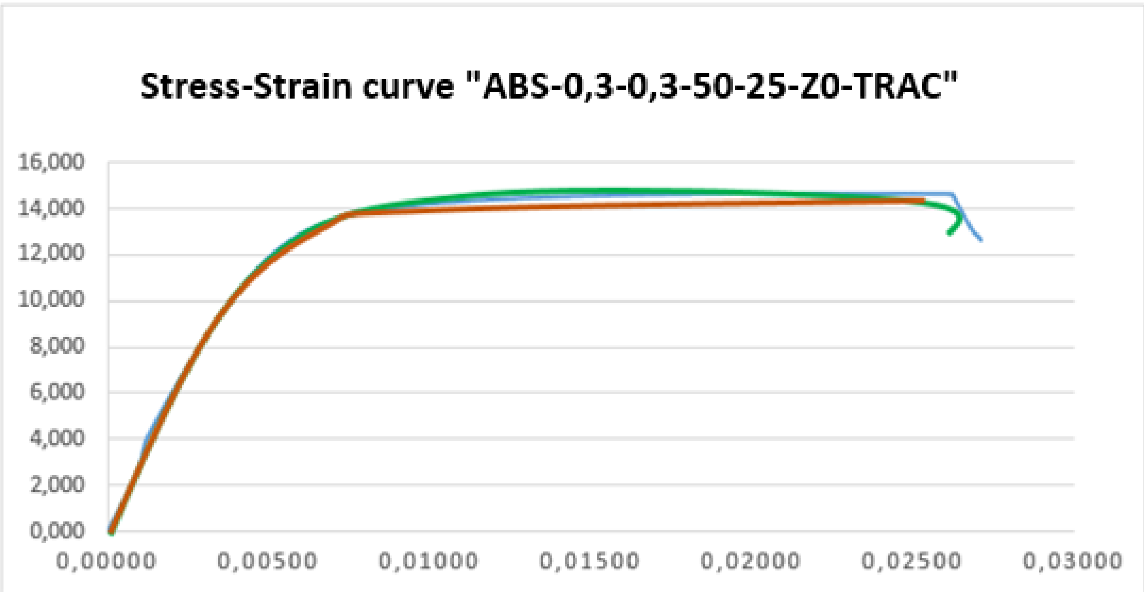

Figure A1.8: Stress-Strain curve "ABS-0,3-0,3-50-25-Z0-TRAC"

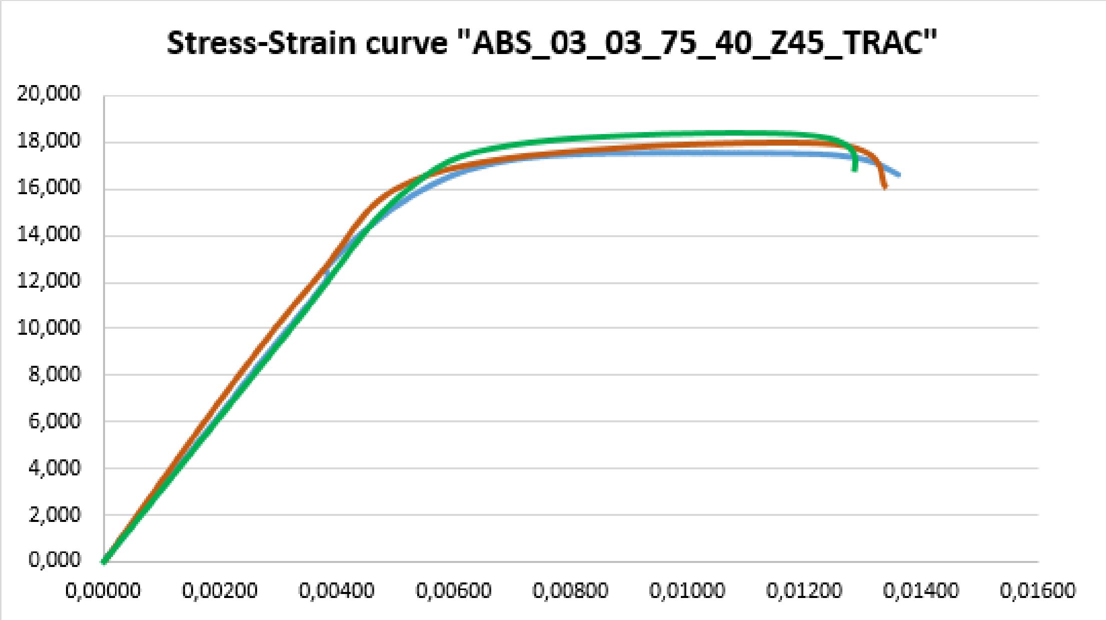

Figure A1.9: Stress-Strain curve "ABS-0,3-0,3-75-40-Z45-TRAC"

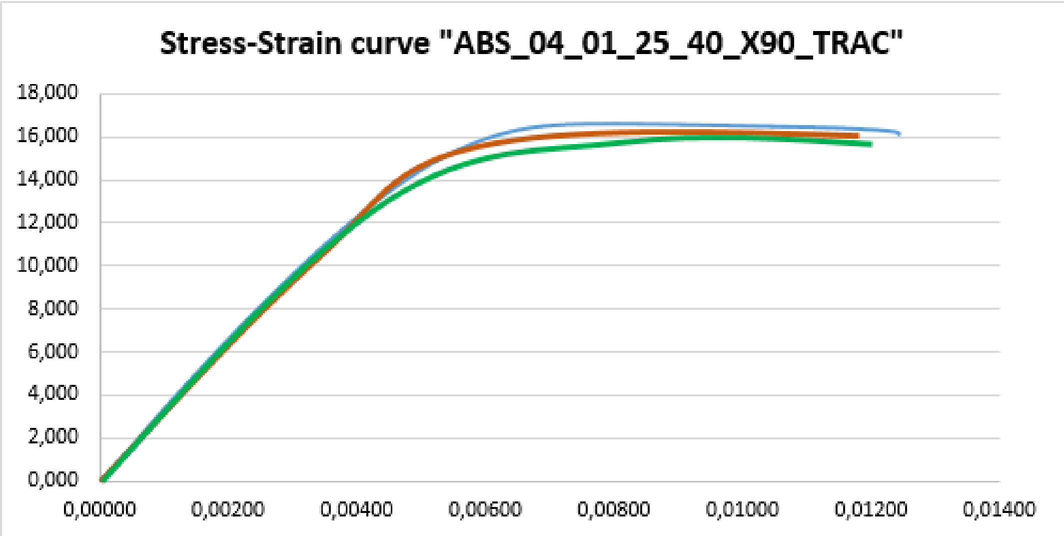

Figure A1.10: Stress-Strain curve "ABS-0,4-0,1-25-40-X90-TRAC"

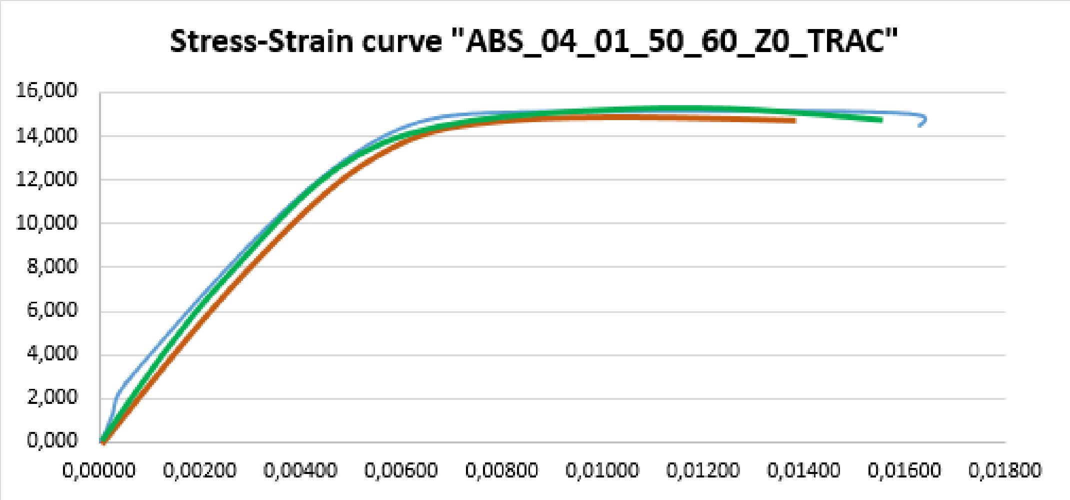

Figure A1.11: Stress-Strain curve "ABS-0,4-0,1-50-60-Z0-TRAC"

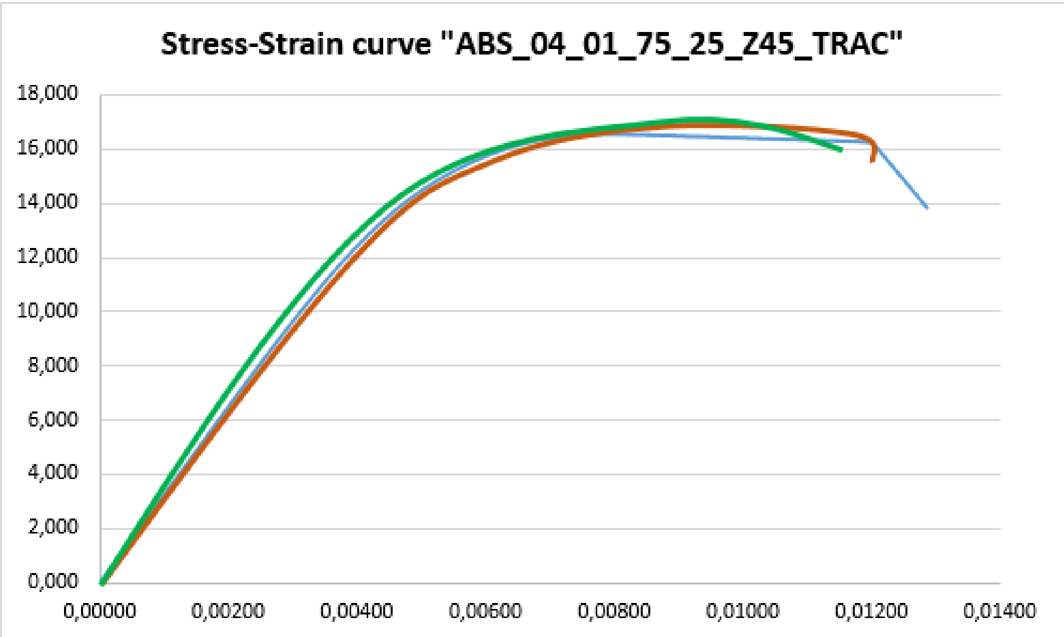

Figure A1.12: Stress-Strain curve "ABS-0,4-0,1-75-25-Z45-TRAC"

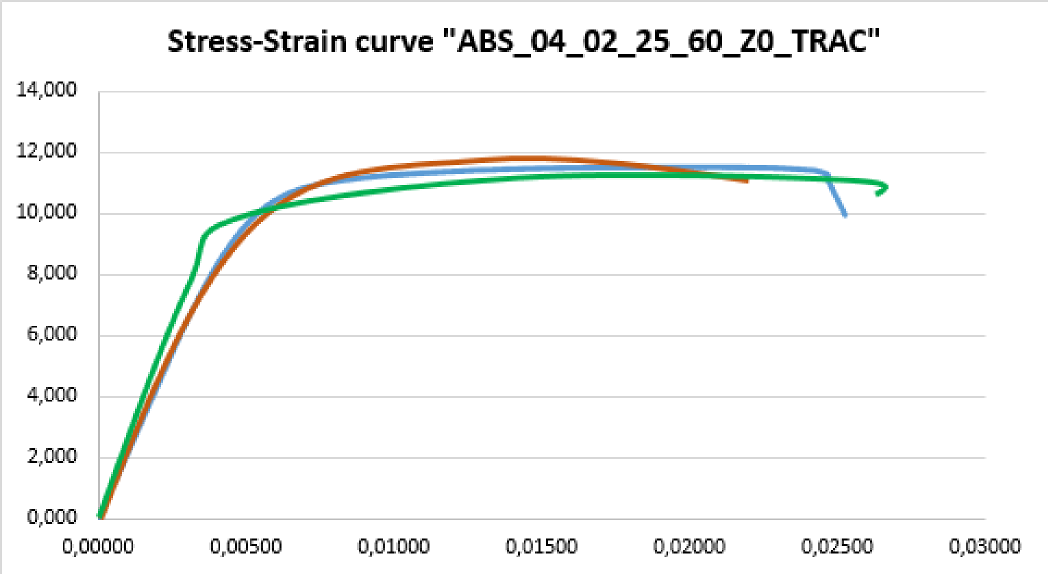

Figure A1.13: Stress-Strain curve "ABS-0,4-0,2-25-60-Z0-TRAC"

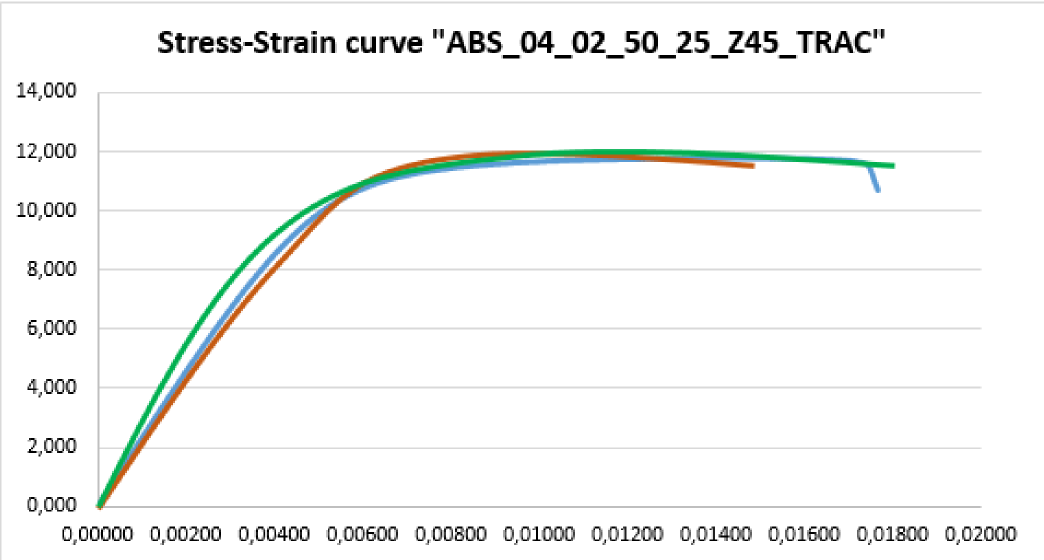

Figure A1.14: Stress-Strain curve "ABS-0,4-0,2-50-25-Z45-TRAC"

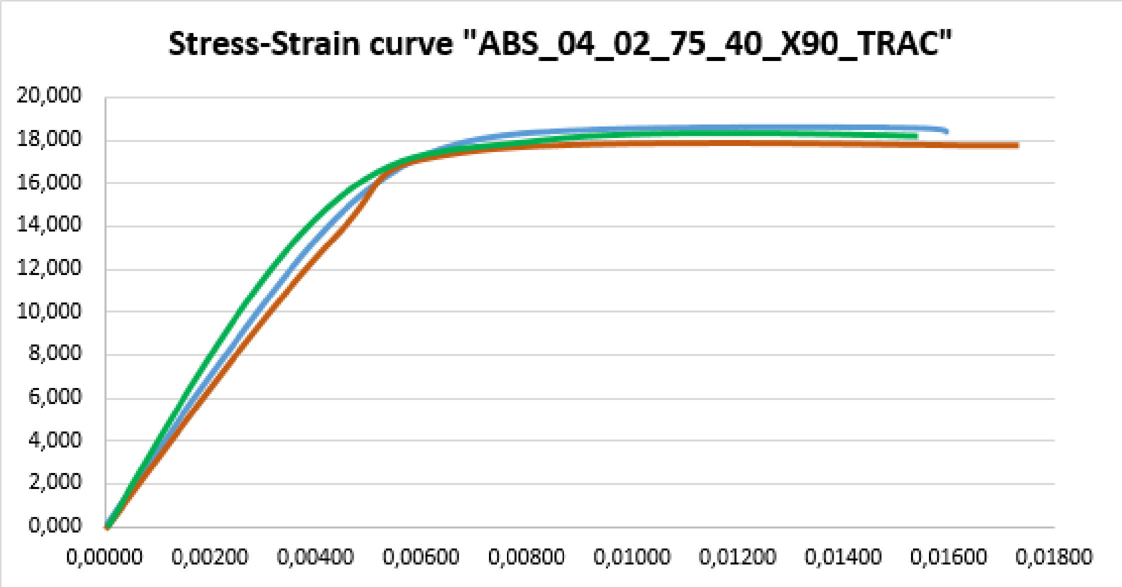

Figure A1.15: Stress-Strain curve "ABS-0,4-0,2-75-40-X90-TRAC"

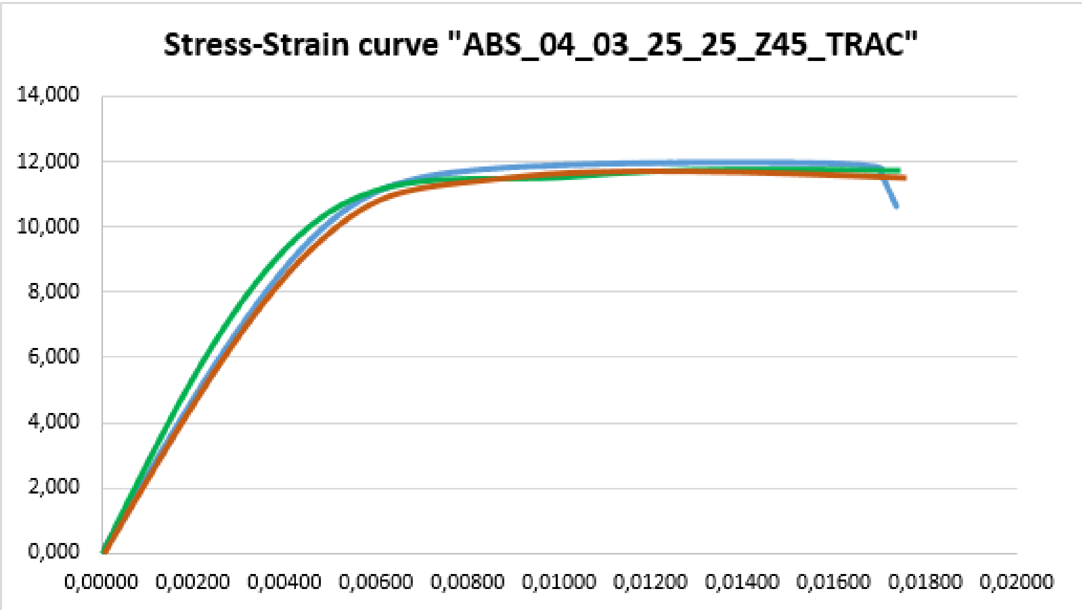

Figure A1.16: Stress-Strain curve "ABS-0,4-0,3-25-25-Z45-TRAC"

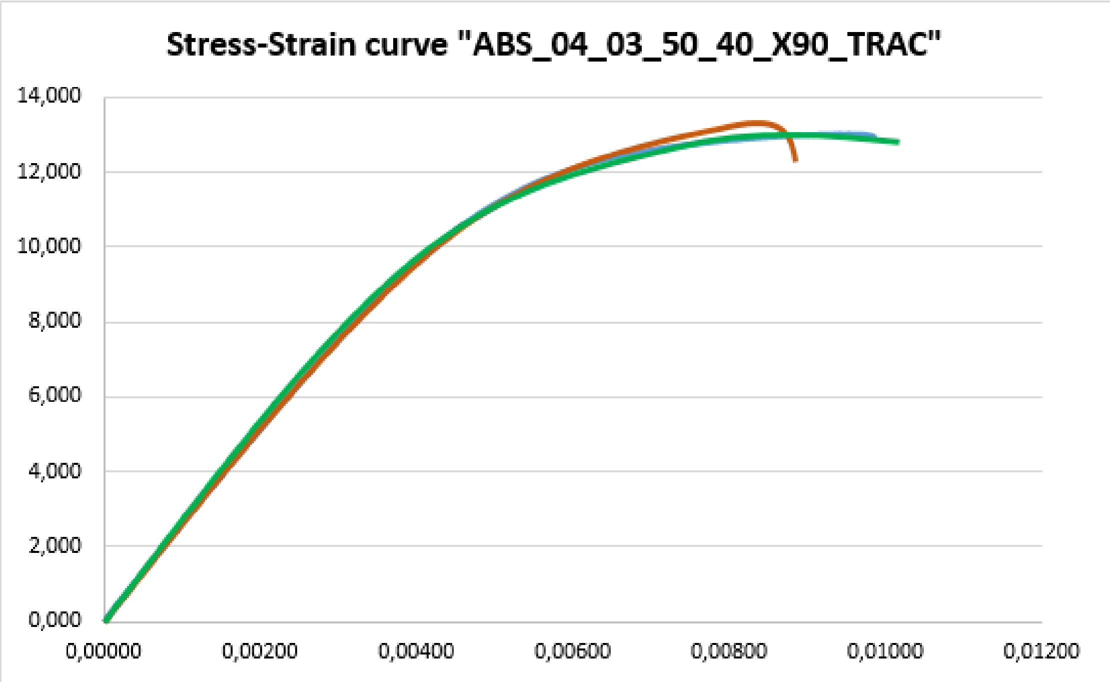

Figure A1.17: Stress-Strain curve "ABS-0,4-0,3-50-40-X90-TRAC"

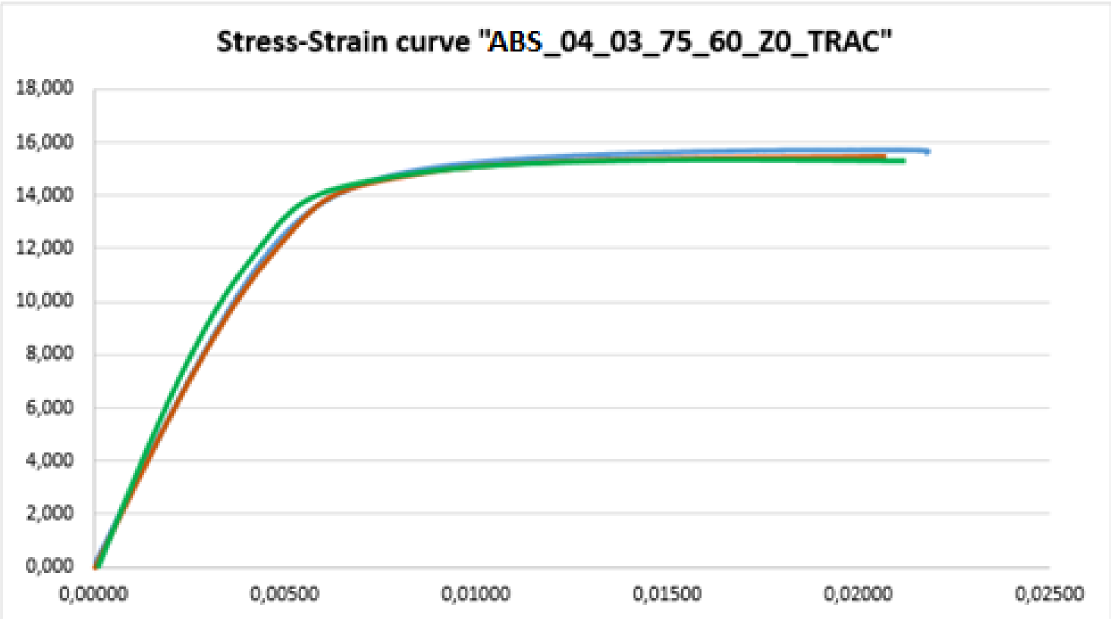

Figure A1.18: Stress-Strain curve "ABS-0,4-0,3-75-60-Z0-TRAC"

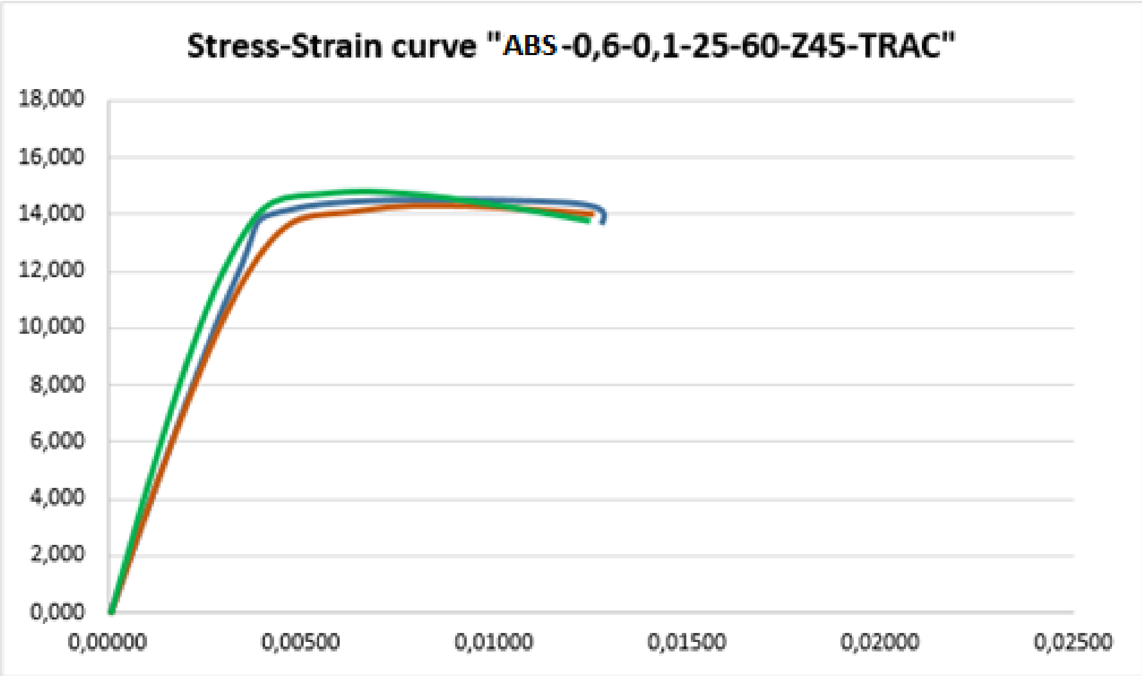

Figure A1.19: Stress-Strain curve "ABS-0,6-0,1-25-60-Z45-TRAC"

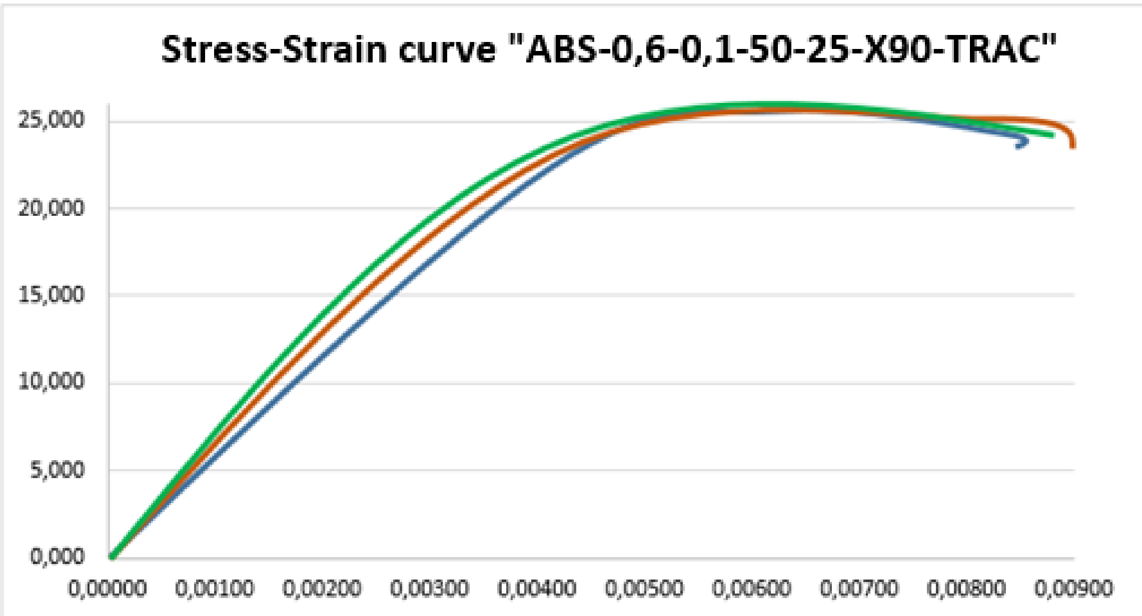

Figure A1.20: Stress-Strain curve "ABS-0,6-0,1-50-25-X90-TRAC"

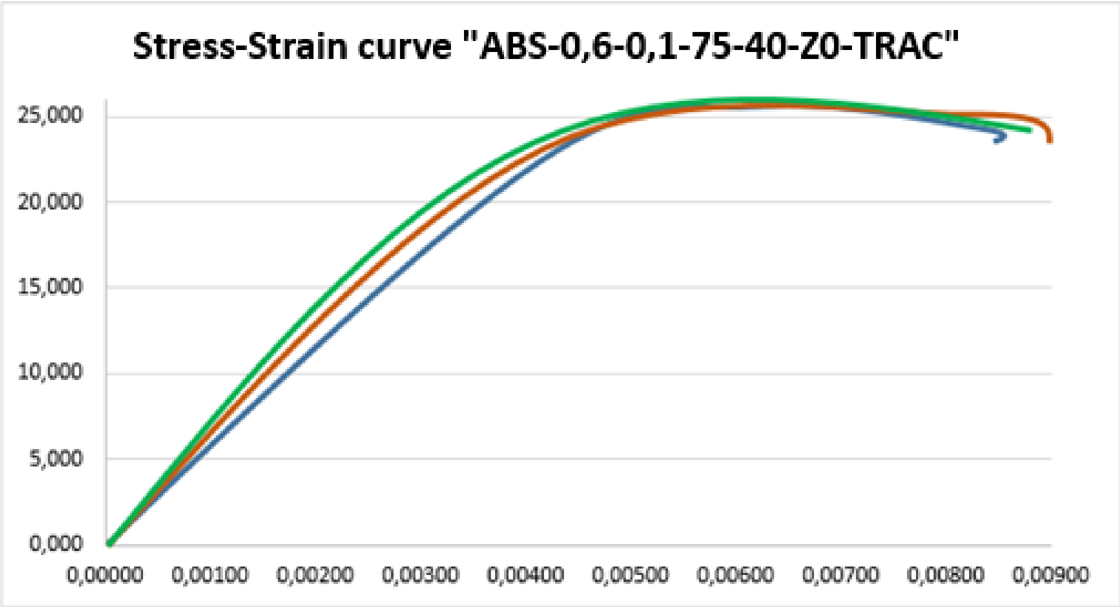

Figure A1.21: Stress-Strain curve "ABS-0,6-0,1-75-40-Z0-TRAC"

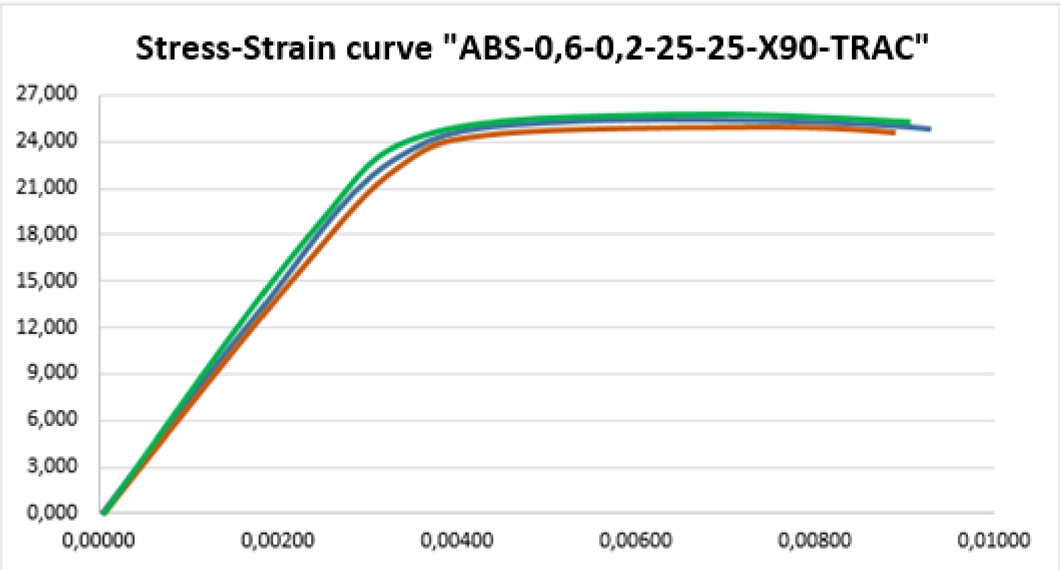

Figure A1.22: Stress-Strain curve "ABS-0,6-0,2-25-25-X90-TRAC"

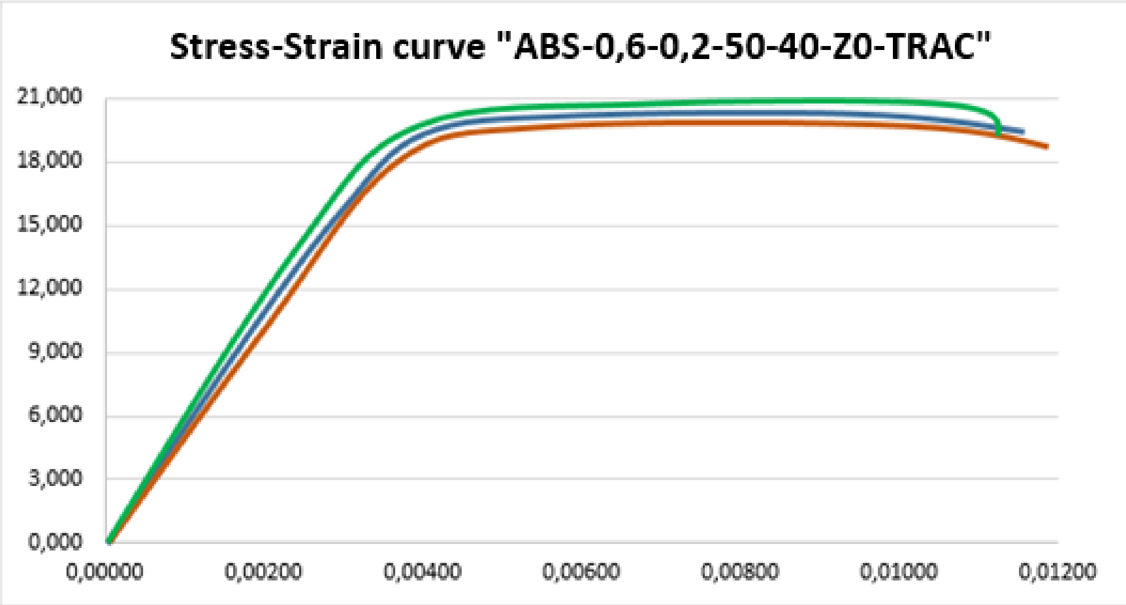

Figure A1.23: Stress-Strain curve "ABS-0,6-0,2-50-40-Z0-TRAC"

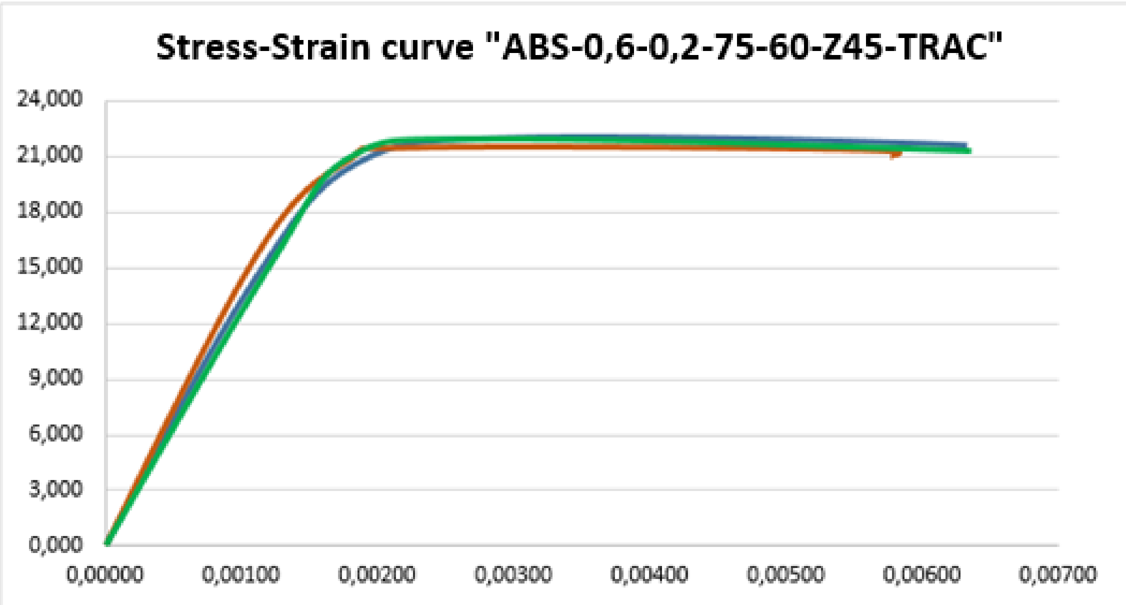

Figure A1.24: Stress-Strain curve "ABS-0,6-0,2-75-60-Z45-TRAC"

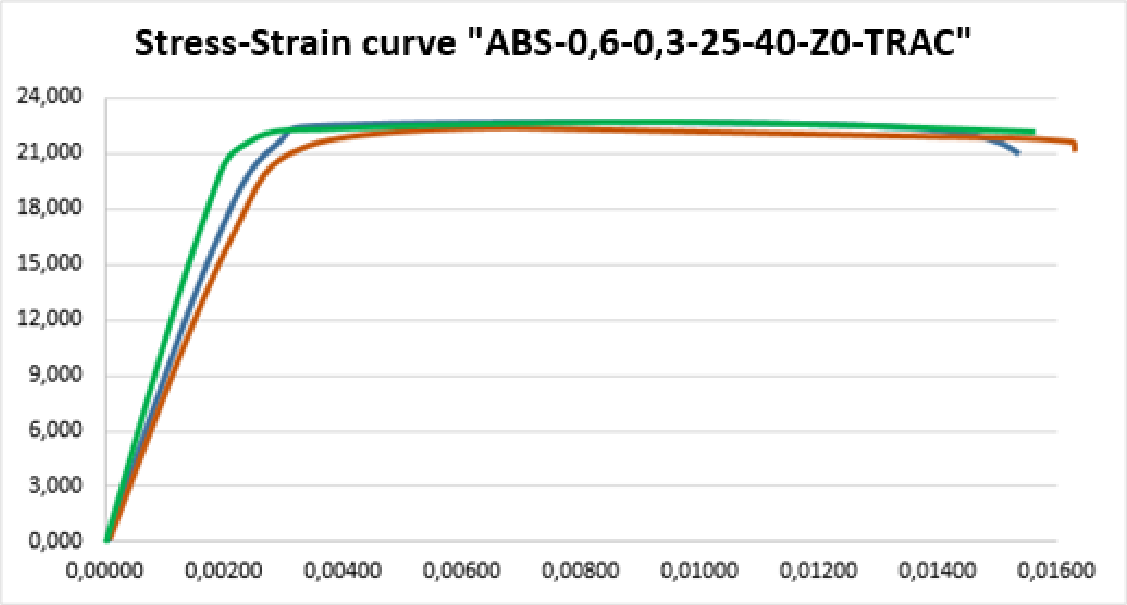

Figure A1.25: Stress-Strain curve "ABS-0,6-0,3-25-40-Z0-TRAC"

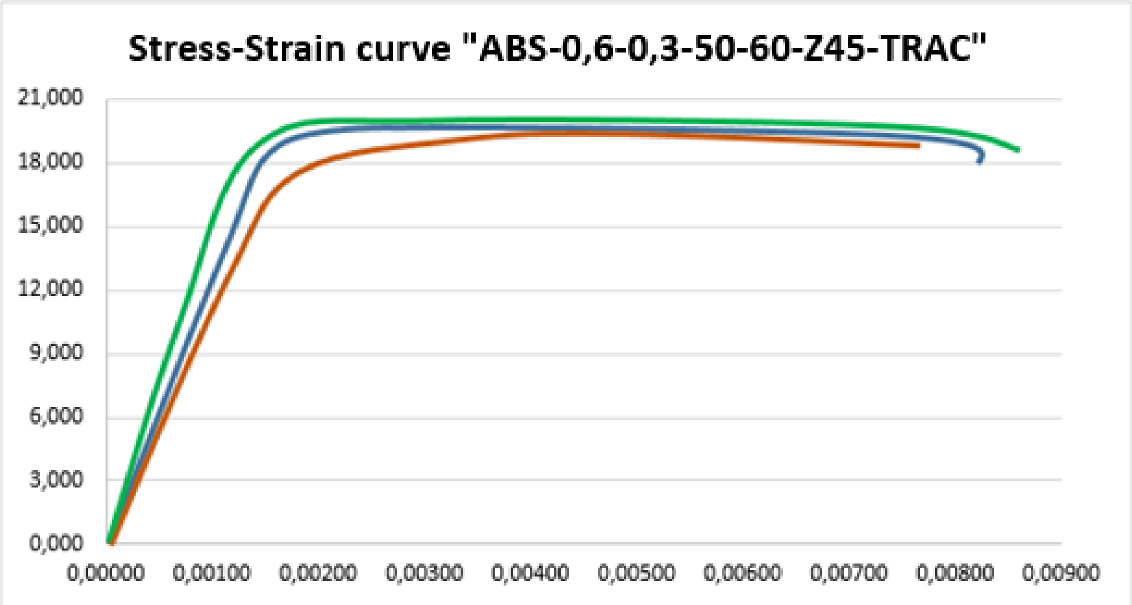

Figure A1.26: Stress-Strain curve "ABS-0,6-0,3-50-60-Z45-TRAC"

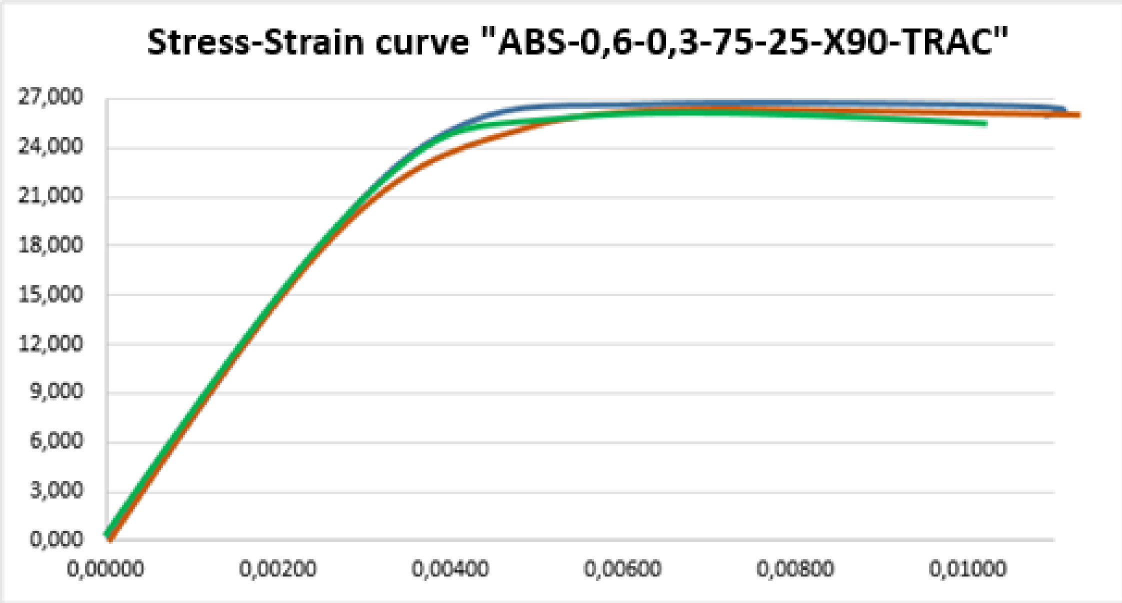

Figure A1.27: Stress-Strain curve "ABS-0,6-0,3-75-25-X90-TRAC"

10. Annex 2: Protocol

10.1. Objective

Exhaustively defining the procedure that must be followed to develop accurately the traction test for the specimens printed beforehand using the technic of Fused Deposition Modelling (FDM).

10.2. Application responsibility and covers

The responsibility of application and cover of this procedure falls onto the personnel (technic and/or auxiliary) that proceeds to do the traction test to the specimens.

10.3. Definitions

ABS specimen: these specimens have been sized according to the norm UNE-EN-ISO-527-1=2012 (Plastics: Determination of tensile properties), even though the specimens are not completely normalized due to the norm referring to completely solid specimens and the ones used in this procedure contain different levels of fill-density. For this reason, the specimens have been slightly modified so the traction tests can be done.

The maximum dimensions are shown in the beneath figure, using millimetres (figure A2.1).

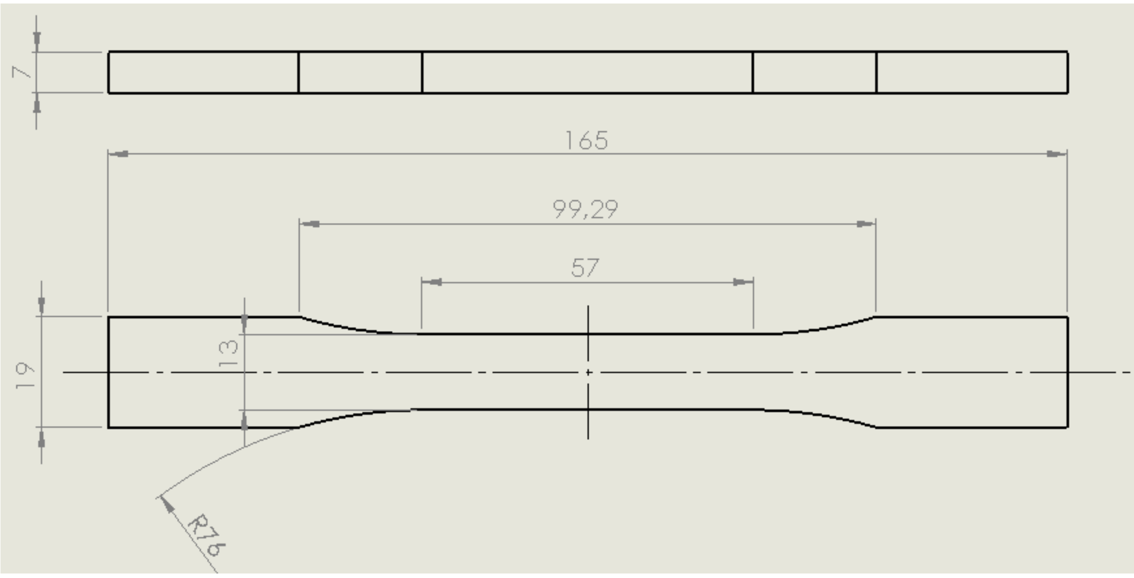

Figure A2.1: Design and dimensions of the specimen

ABS: Acrylonitrile butadiene styrene is a terpolymer made by polymerising styrene and acrylonitrile in the presence of polybutadiene. The most important mechanical properties of ABS are impact resistance and toughness. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance. The impact resistance can be amplified by increasing the proportions of polybutadiene in relation to styrene and also acrylonitrile, although this causes changes in other properties. Impact resistance does not fall off rapidly at lower temperatures.

Tools: instrument designed and created to develop a specific function.

Digital micrometre: also known as micrometre screw gauge or simply Palmer, it's a measurement instrument the functioning of which is based in the micrometre screw and its used to measure the dimensions of an object with high precision, on the order of hundredths of millimetres (0,01) and thousandths of millimetres (0,001 mm).

10.4. Description

MATERIAL AND EQUIPMENT

- Black indelible marker.
- Annotation handbook and pen.
- Adhesive tape.
- Precision scale.
- Digital micrometre.
- ABS specimens.
- Traction MachineMicrotest EM2/20.
- 25 kN load cell.
- Acquisition data system Spider y Microtest.
- Screwdriver kit to fix the cabling to the Spider acquisition data system.
- Microtest software, Catman 4.5.
- Jaws.
- DD1 Red Extensometer.
- DD2 Blue Extensometer.
- Line/Gauge to align the jaws.
- Wrench.
- Spanner wrench 80-120.
- Spanner wrench 35-50.
- Open end wrench 20-22.
- Ring spanner 22-24.
- Ring spanner 24-27.

10.5. Sample separation

1. Every specimen must have written in every side the number of identification, with its proper naming so it's easy to know with what printing configuration we are working with. Furthermore, if we are working with different specimens with the same configuration, they must include in each of their bases the chronological fabrication number so we can differentiate them. To do this, we will use an indelible marker (Figure A2.2).

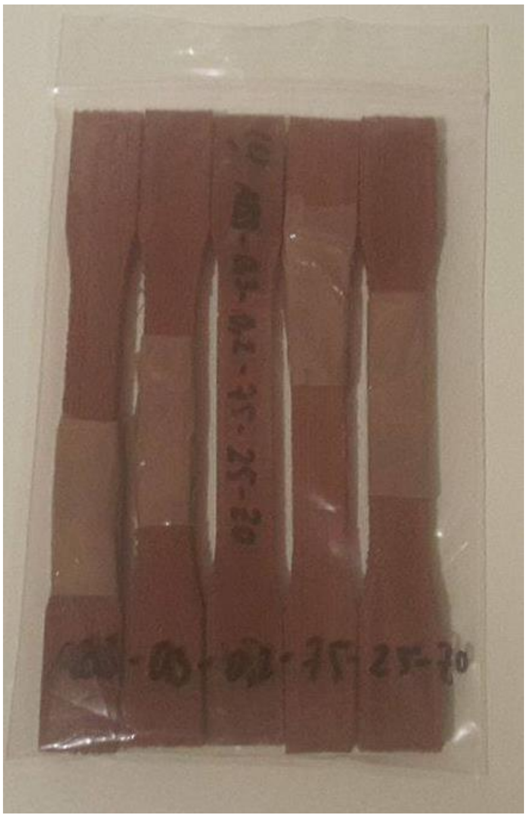

Figure A2.2: Specimens naming

2. The next step consists in doing the metrology of every specimen using the digital micrometre. The metrology will be done to the area where the tests are going to focus. This area is the one shown at figure 1 that has a 57 mm length.

The next steps show how the micrometre or Palmer has to be used to obtain a satisfactory measure. In Figure A2.3 we show an image of the Palmer that we are going to use and in Figure A2.4, a comparison with the parts of a conventional Palmer.

Figure A2.3: Micrometer or Palmer

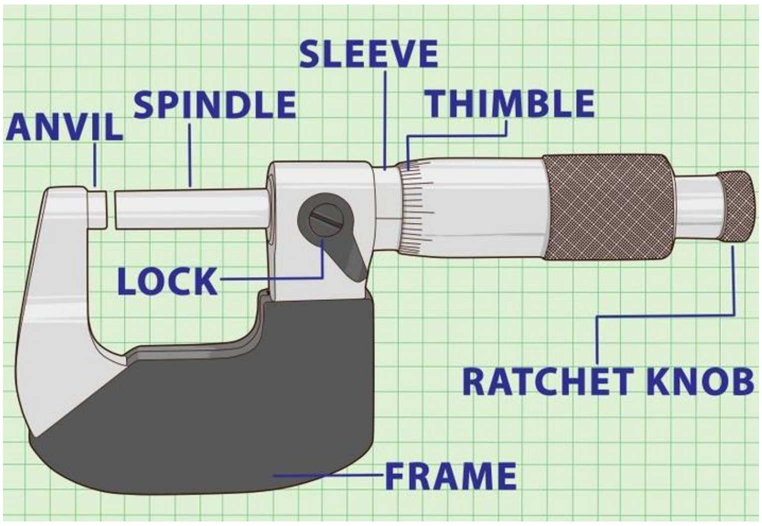

Figure A2.4: Main parts of the micrometer

- Verify that the micrometre is clean. Don't forget to perfectly clean the measuring sides of the spindle and the anvil, or you will not get exact measures. To perfectly do the measurement, it is essential that the object that is going to be measured is clean from oils and dust.
- Use de micrometre adequately. For a good micrometre use, fix the micrometre to a support, this way we will get the body to handle steady during the measurement and we will not have to worry about holding it.
- First, verify that the zero is aligned. To do this, bring the micrometric spindle until reaching the anvil, then press the micrometre red button to set the zero, this way, we will have it calibrated. We should see that a zero appears in the display screen.
- The measurements will be done along the 57 mm area shown in Figure A2.1. We will measure the width (Figure A2.5) and the thickness (Figure A2.6) 5 times each.

To get good results, before the spindle touches the object, spin the thimble smoothly, with your fingers, when the spindle finally touches the object, spin 3 or 4 times the thimble at a uniform speed.

This is important because if we approach the object fast, the spindle could apply excessive force to the object and the measurement could be wrong.

Figure A2.5: Width measure

Figure A2.6: Thickness measure

- When the measurement is complete, separate the spindle from the object spinning the thimble in the opposite direction. Before doing that, write down all the measurements in a digital file or in a paper to have control over the process and so you can work with the data obtained afterwards.

3. To conclude with the preparation of the test, we will weight every specimen using a precision scale precise enough to read thousandths of grams (Figure A2.7). Before doing any weighting make sure to tare the scale (yellow button). We will also include this data into our data sheet.

Figure A2.7: Weight measure

10.6. Machine servicing

1. Turn on both computers. The computer on the left will be the one connected to the Microtest machine data acquisition system, which software will allow us to control the machine. On the other side, the computer on the right will contain Spider's acquisition data system, which we will use to obtain the data from the test because it is more precise than the previous one.
   With the left computer we will control the test's execution parameters while the computer on the right we will acquire the data that we will have to analyse.

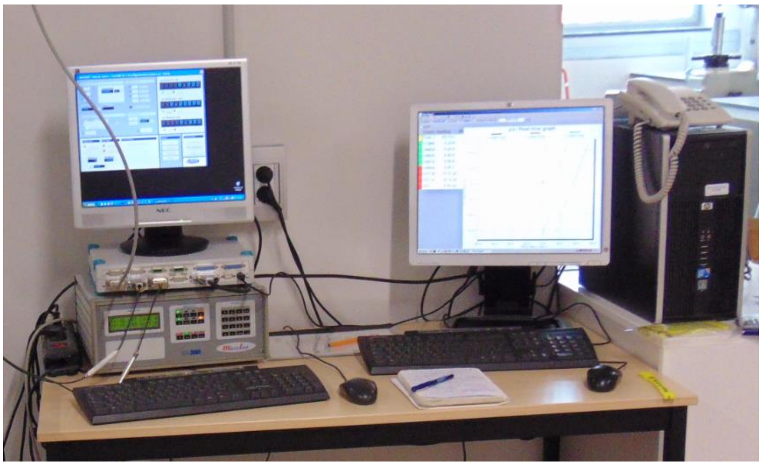

Figure A2.8: Computer setup

2. Spider's acquisition data module connection.

 - First we will connect to the electric grid the Spider's power transformer using a PS/2 cable (Figure A2.9).

Figure A2.9: Spider connection

 - We will activate its own power supply (Figure A2.10).

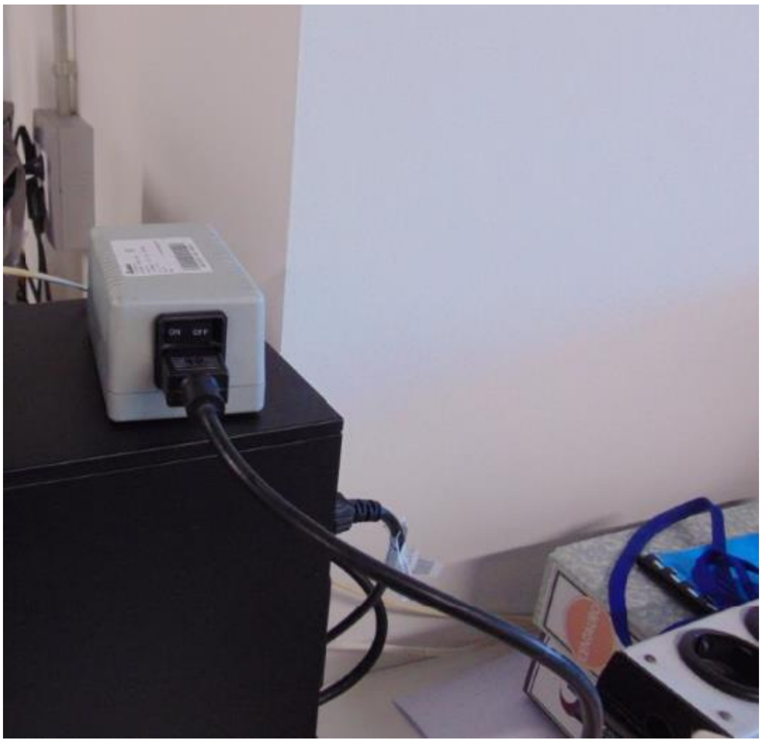

Figure A2.10: Power supply

- Turn on the Spider's module pressing the button placed at the back of the device.
- Next we will connect the parallel port cable LPT from the module (where the PC indicates) to the right computer (Figure A2.11).

  The parallel port LPT consists of 8 wires that transfer 1 byte every clock pulse. That's the reason why they are faster than the ports in serial connection (which transmit 1 bit after the other) and that's why we use them in this Project.

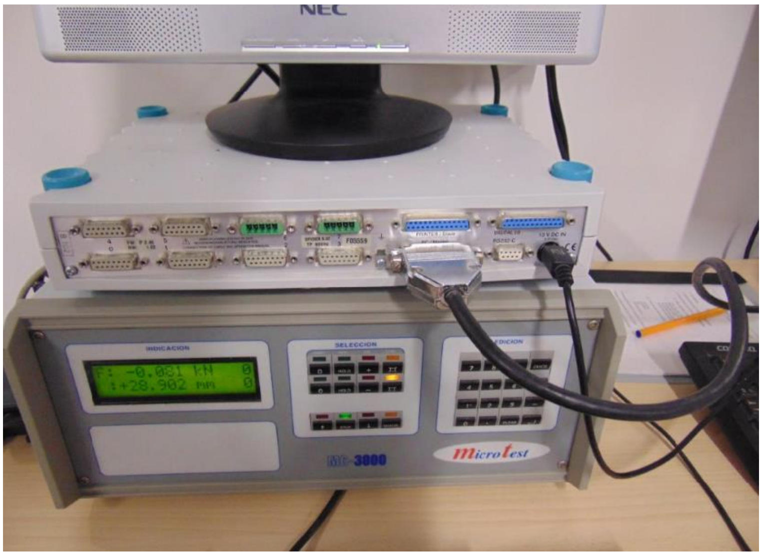

Figure A2.11: LPT cable connection

There are USB multiplexed USB cables that have been able to accelerate data transfer even though they are only made of 2 wires, if we could have used them in our experiments the data would have been even more accurate.

Some port can be swapped to another but the software is programmed to expect the established configuration and if we would like to change it we would have to change the parameters in the program (Figure A2.12).

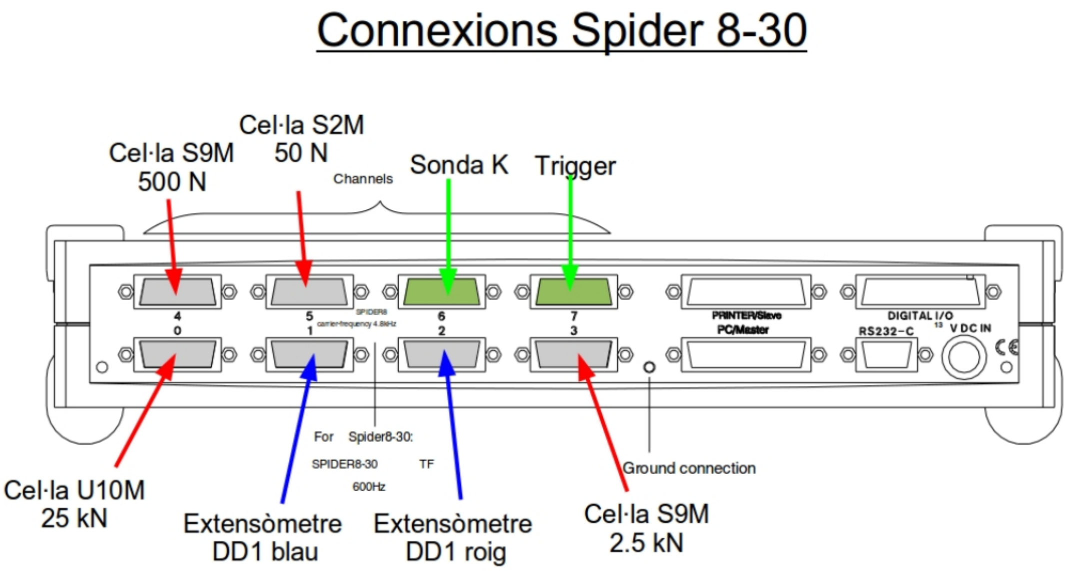

Figure A2.12: Spider connections 8-30

- The last thing is the connection of the extensometers. To get the best measurements of the lengthening, we will use 2 extensometers and the software will calculate the mean between the movements that happened during the traction test. To distinguish the 2 extensometers, we will mark them with 2 different colours; this way we know where we have to place them according to the previous instructions.
  The cables and connectors include a screwing fixing system that makes impossible any disconnection while the software is getting the data from the tests (Figure A2.13).

Figure A2.13: Screw fixing system

3. Preparation of the Microtest EM2/20 traction machine.
   - First, make sure that the pressurised air's shut-off valve is closed, this way we will be able to manipulate the movable parts of the machine without any danger (Figure A2.14).

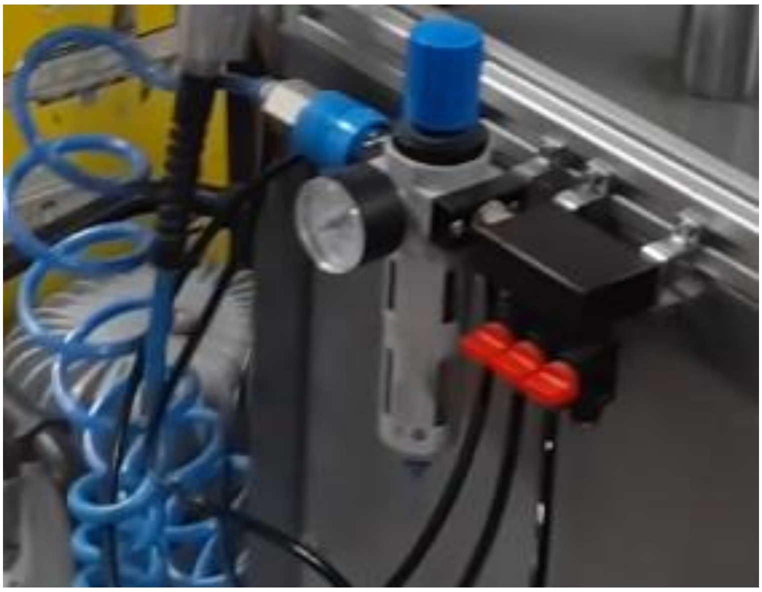

Figure A2.14: Pressurised air valves

- Next, disconnect the plug that comes from the upper jaw to the pressure system's control.
  To do this press the blue nozzle from the air entrance upwards and then extract the tube pulling down.

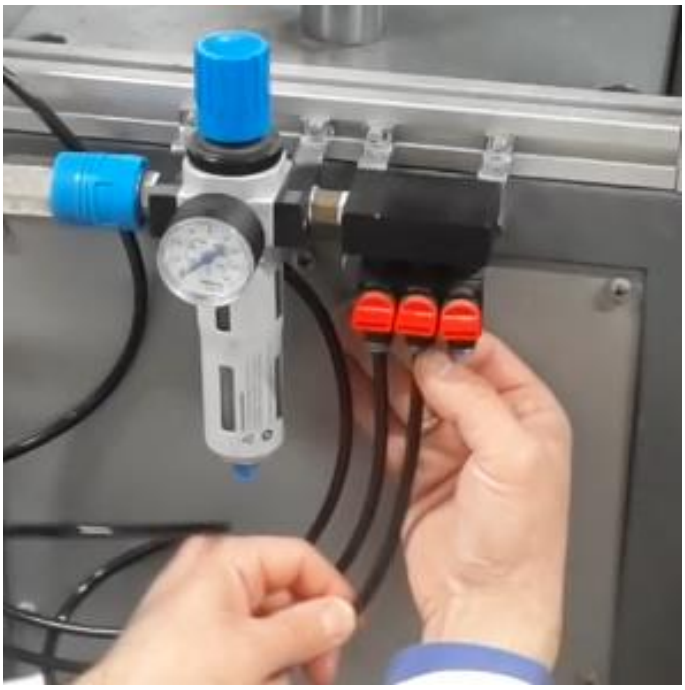

Figure A2.15: Pressurised air tube connection

We take off this tube so we can clean the working area and then unscrew the upper section of the jaw-cell assembly to install the cell that we will use for our tests.

- To be able to remove the superior jaw and add our cell, we must disassemble the previous assembly composed by and adaptor between the force transducer and the superior jaw using thread and a bolt.

  To do this we will unscrew the superior thread, we will remove the bolt and then we will be able to remove the superior jaw. After this, we will remove the adaptor threaded in the force transductor (Figure A2.16).

Figure A2.16: Jaws

- The next step will be to assemble our 25 kN load-cell. Beforehand, it is important to mention that the load-cell can hold traction stress but not torsion stress, this means that we have to be really careful when we have to assemble and disassemble it.
  To do the assembly we will have to follow the next steps:
  - Screw the load cell with your hands to the max of its capability, gently (Figure A2.17).

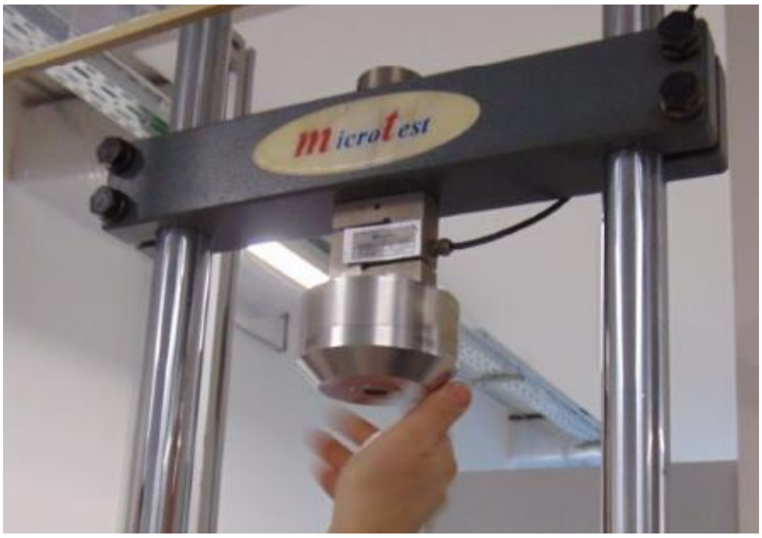

Figure A2.17: Load cell

- With the use of the 80-120 spanner wrench, and the help of a 20-22 wrench we will finish to adjust the cell with the transductor applying enough force for them not to move (Figure A2.18).

Figure A2.18: Load cell fixation

- Next we will put the coupler with our hands and then we will tighten it using both the 80-120 and the 35-50 spanner wrenches (Figure A2.19).

Figure A2.19: Coupler fixation

- We couple the superior jaw to the coupler, we align them so that we can insert the bolt and then we block the assembly using a thread. We gird the assembly using the 24-27 ring spanner and the 35-50 spanner wrench, always being careful that we don't apply to much force to the assembly (Figure A2.20).

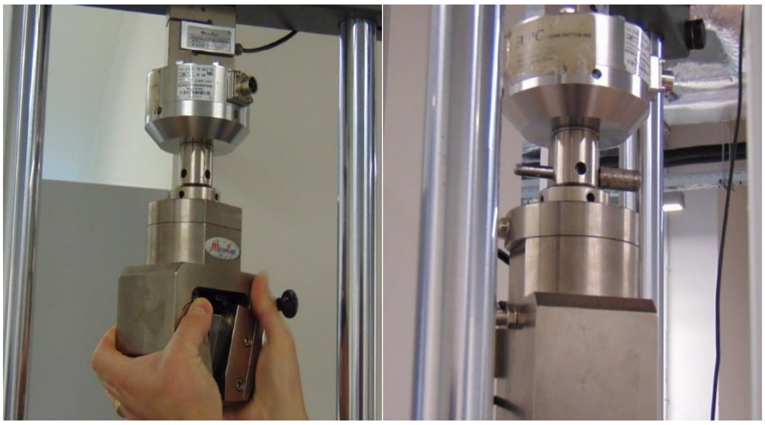

Figure A2.20: Assembly gird

- The next step is to connect again the pressure tube that we disconnected previously to the superior jaw so we could assemble everything. After that we will connect it again to one of the pressurised air entrances (Figure A2.21).

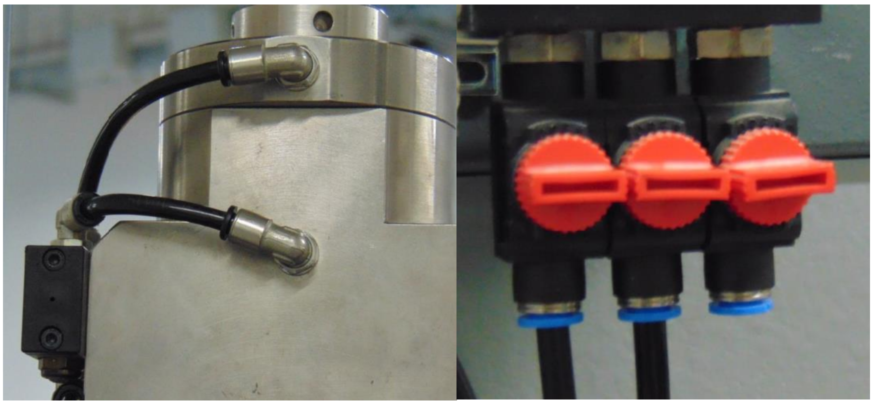

Figure A2.21: Pressure tube connection

- To continue, we connect the load-cell to the Spider's acquisition data system using a DS/MS cable. To connect it to the load-cell we must press it and twist it, this way it will stay well attached; the other extreme of the cable will go plugged to the Spider's system, screwing to its module (Figure A2.22).

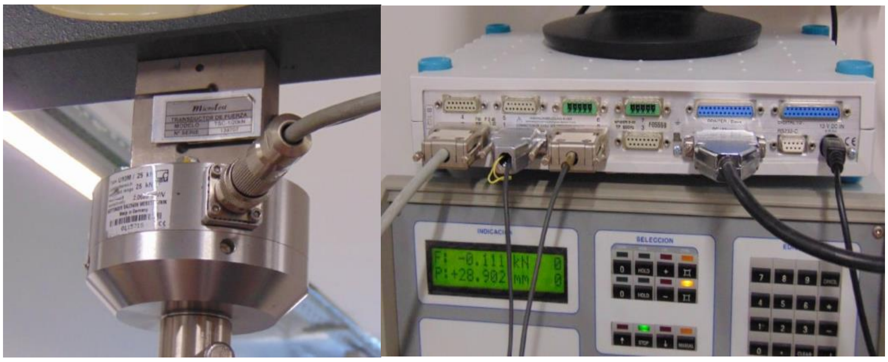

Figure A2.22: Load cell and Spider's connection

- Jaws alignment:

  We align the jaws to assure the verticality of the longitudinal axis where they slide and this way avoid any unwanted rotations while doing the tests.

  - Firstly, we will open the shut-off valve connected to the jaws, which comes from the pressurized air from the deposit.
  - We will provide the system with a little pressure so that the jaws can hold the alignment caliber between them (Figure A2.23).

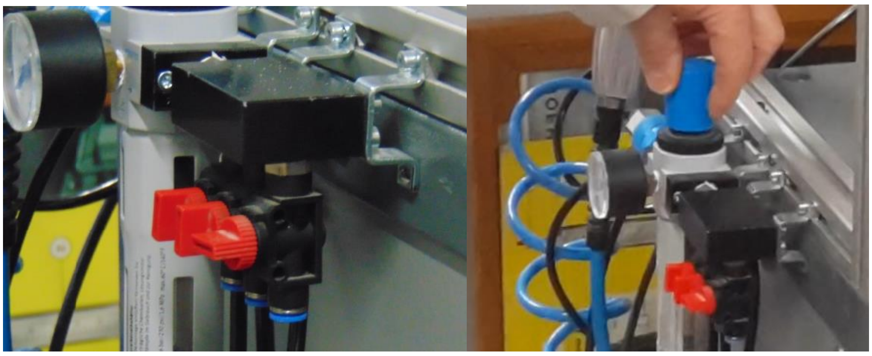

Figure A2.23: Opening the valve to apply a little pressure

  - We will fix the power guide (caliber) to the superior jaw, to do this we will open the activation valve to activate the jaw, we will insert the guide and we will block again the valve (Figure A2.24).

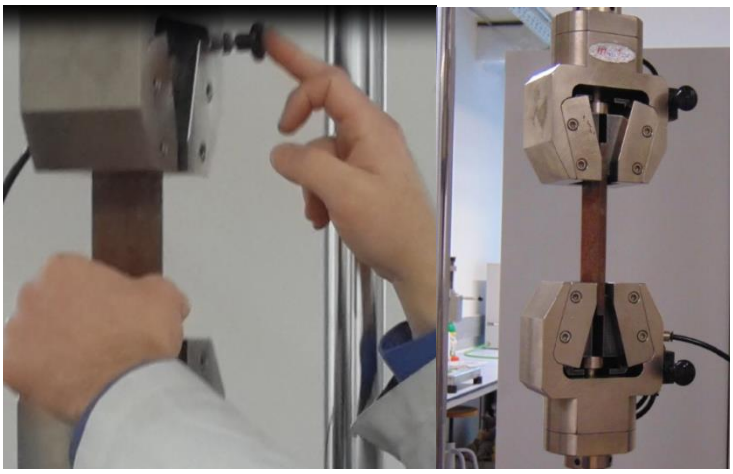

Figure A2.24: Jaw alignment

- To get a minimum distance required between the jaws, we will move the inferior assembly (inferior jaw) until it reaches the guide's inferior limit set by the machine itself (Figure A2.25).

Figure A2.25: Inferior limit

- To move the inferior jaw, we will have to go to the left computer's "Control Panel". When we double click it, it will open the Microtest's software to control the parameters of the machine (Figure A2.26).

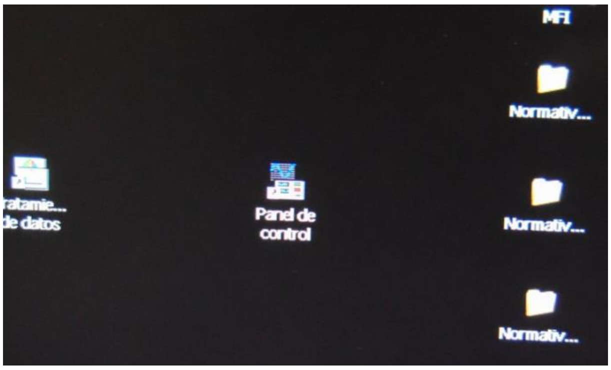

Figure A2.26: Microtest software's shortcut

- We will activate the joystick by clicking on its button. We will see a green light when we activate it.
  We will modify the speed to 162 mm/min (maximum speed allowed) writing this value in the speed's panel and then pressing "ENTER" in the keyboard to confirm the speed change.
  Also, we must click the movement configuration that we want, selecting that we want an upward movement (Figure A2.27).

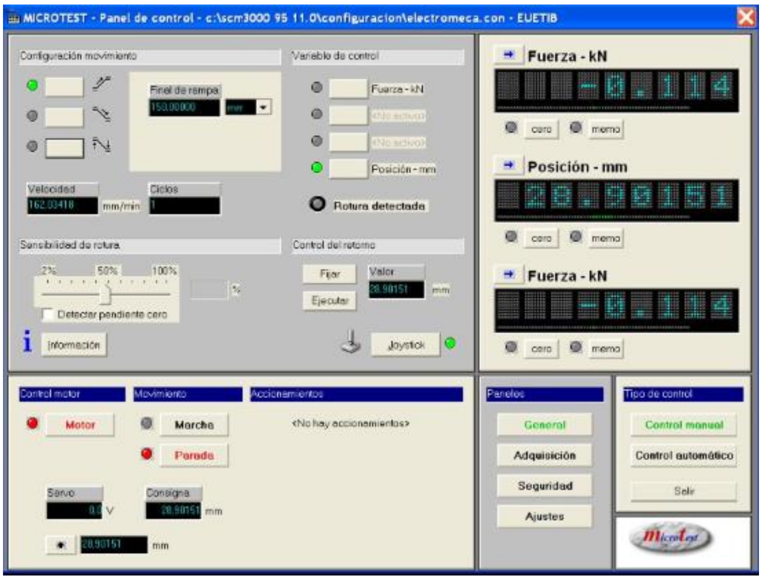

Figure A2.27: Microtest option screen

The only thing left at this point is to activate the ON switch of the machine, turning the black button to the right (from 0 to 1). After doing this we will be able to use the UP and DOWN buttons freely to move the inferior jaw to its superior limit (Figure A2.28)

Figure A2.28: Traction machine's buttons

Once we reach the superior limit, the software will warn us displaying a message that says that we reached said limit (Figure A2.29).

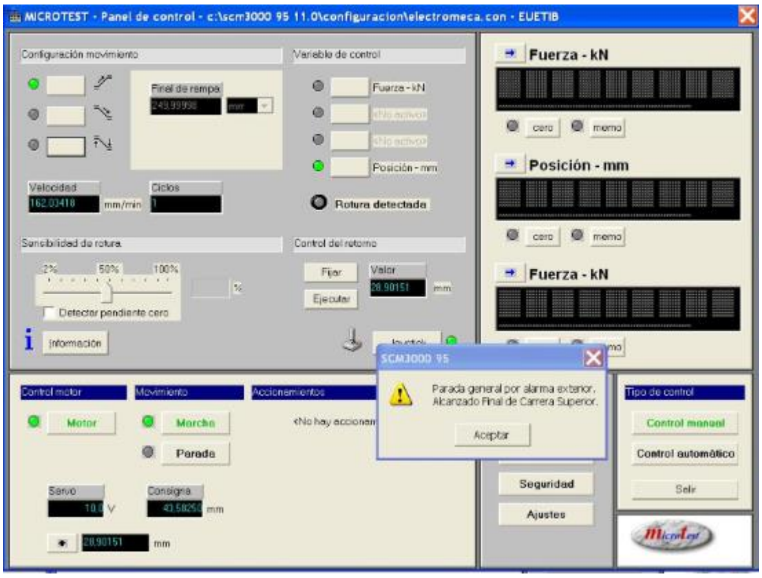

Figure A2.29: Superior limit reached message

- We will block the inferior jaw's valve and we will make sure that the alignment caliber is firmly trapped between both jaws. Then we will give maximum air pressure until we reach 6 bar (Figure A2.30).

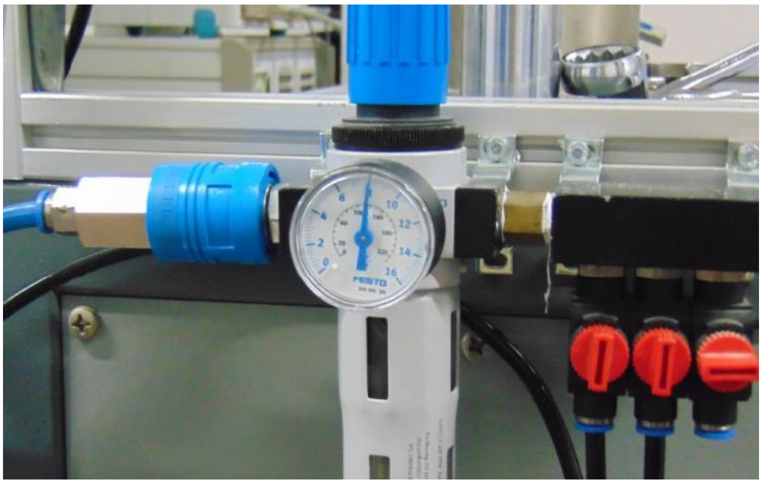

Figure A2.30: Maximum air pressure

- To conclude the alignment, we must fixate the thread in under the inferior jaw using the 20-22 wrench and the 24-27 ring spanner (Figure A2.31).
  Once it's done, we will make the pressure 0 again. The machine is finally well aligned and ready to do the tests.

Figure A2.31: Final alignment adjustments

10.7. Traction test

- Setting up Microtest SCM3000-Control Panel (left computer).
  - This computer has already been set up previously when we did the alignment. We should see the Microtest SCM3000's "Control Panel" in the computer screen (Figure A2.32).

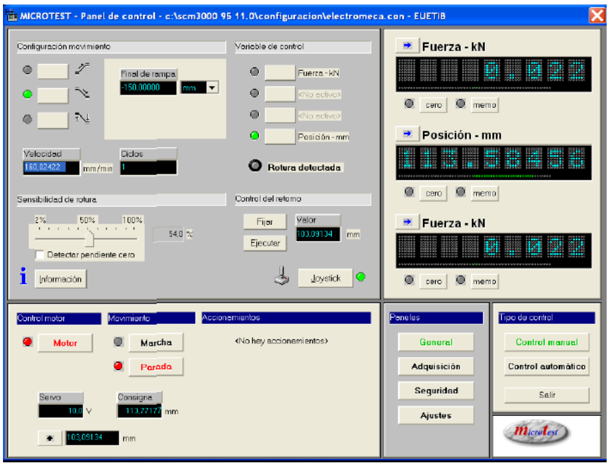

Figure A2.32 Microtest's control panel

- Spider's Catman Software set up (right computer).
    - Open the software "Catman 4.5" from the Spider module.
    - In the emerging window "ProgramLauncher" select "Professional" mode and then click Start (Figure A2.33).

Figure A2.33: Catman's program launcher window

- In the following screen, select "OK". Let it load until the window disappears and the final screen opens (Figure A2.34).

Figure A2.34 Catman's program info screen

- Select “File+Open Project” (Figure A2.35). Next, click in the “CATMAN” folder and a “file selection” menu should appear. In this menu we select “Traccióambcamera I extensometer-60 Hz” and we click “OK” (Figure A2.36).

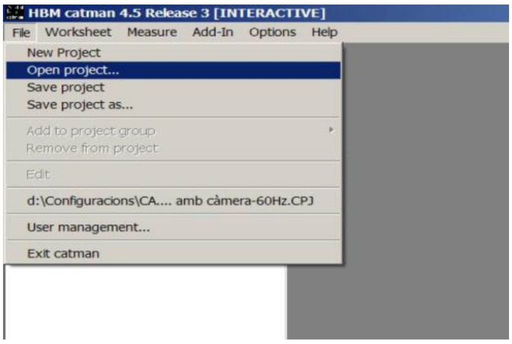

Figure A2.35: Open project option

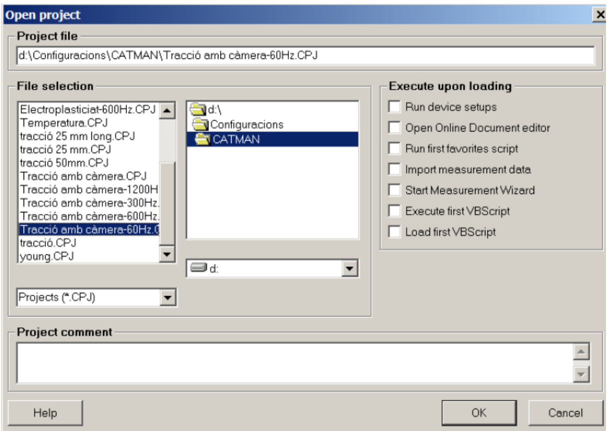

Figure A2.36: Tracció amb camera option

- Select “Workseet -> I/O Definition”. It will appear a window where we can see “I/O Channels” and then make sure that all the devices appear on the list (Figure A2.37.).

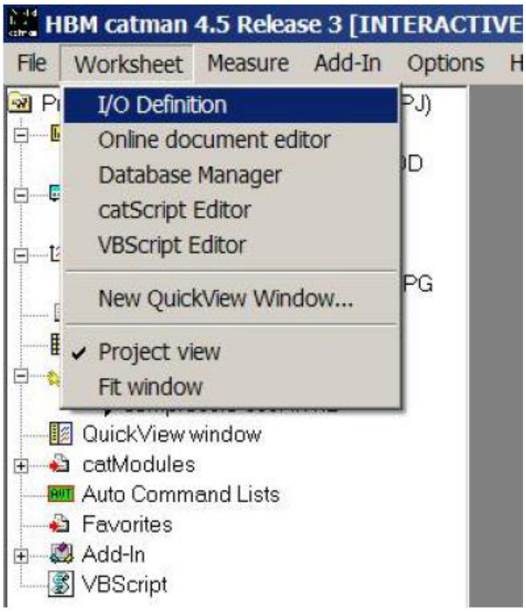

Figure A2.37: I/O Definition option

- We will select “DeviceSetups” in the left menu and then we will click on “Tots-els-sensors-60Hz.s8”. An emerging window will appear with a section where all the sensors will load (Figure A2.38).

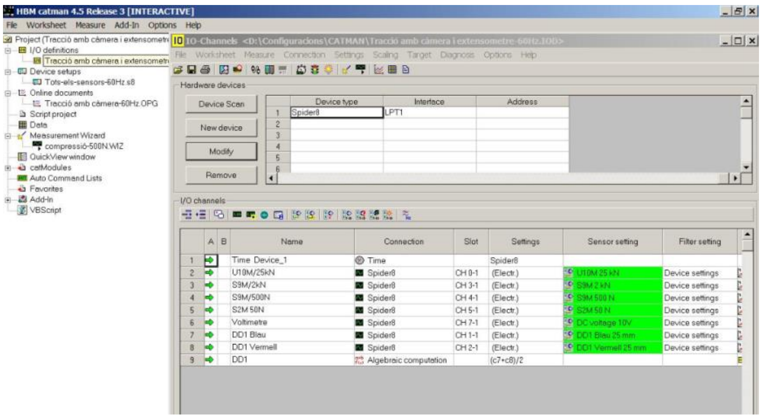

Figure A2.38: Sensors window

- Again we will go to the left menu and open the “Measuring” section selecting el “+” symbol that will appear at the side. Then we will double click “Data Logger” (Figure A2.39).

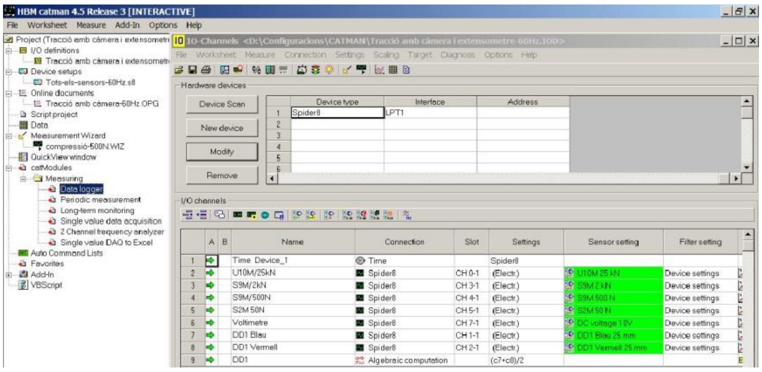

Figure A2.39: Sensor's window

- Another emerging window will appear. In the “Visualitzationwindow” select “y(x) Real-time graph”, in “Save to database” select “Save all activate channels” and in “online export” select “Donotextport”. To finish, select “Run” (Figure A2.40).

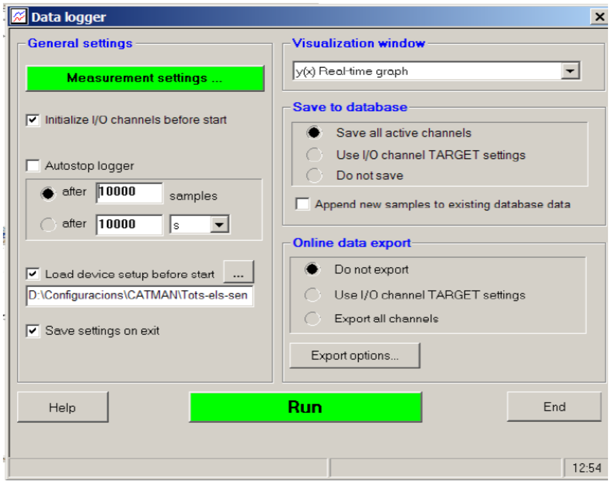

Figure A2.40: Visualization window

- A window with the name “Data Logger” a will open with a graph on it. On top of the graph 3 lines should appear; a blue one, a red one and a green one where it reads U10M/25Kn. If this is not the case, right click on top of the graph and select “Data Sources” in the appearing menu (Figure A2.41).

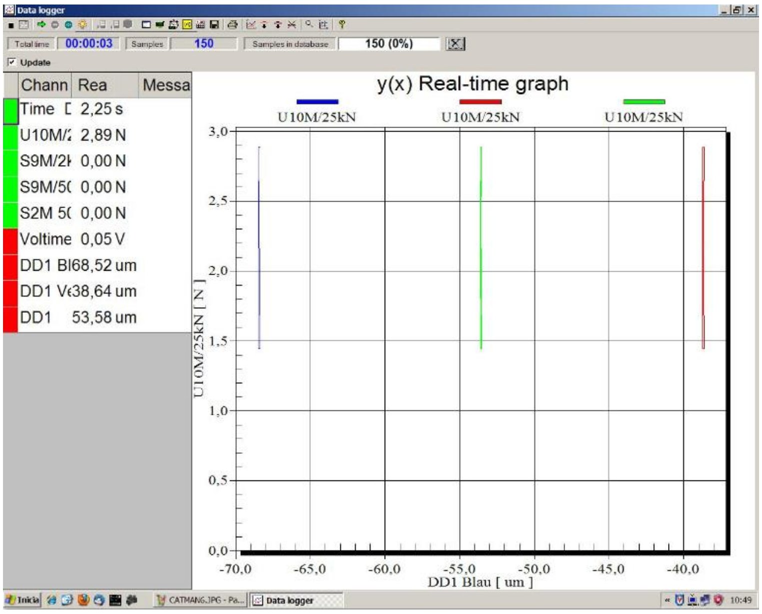

Figure A2.41: Graph's window

- We will see an emerging window named "Configure 2D scientificgraph". In the bottom left menu in the "Left Y Axis" section the cells that are being represented in the graph will be shown. Select the cell that we don't want it to appear in the graph and select "RemovePlot".
- If the cell isn't shown, in the section "X Data sources" from the emerging window select "Time Device_1" and in the section "Y Data Sources" select the cell that we want.
- In the bottom left side, it will appear the name of the cell and a colored section. If we desire to change the color, click on top of it and select the wanted color. Select "Add Data Plot".
- Make sure that the bottom left side only shows what we need. After we make sure of it select "Apply".

- Test execution
  - It is really important to make sure that there is not pressurised air going into the system so we can manipulate without any risk the machine's mobile elements (Figure A2.42).

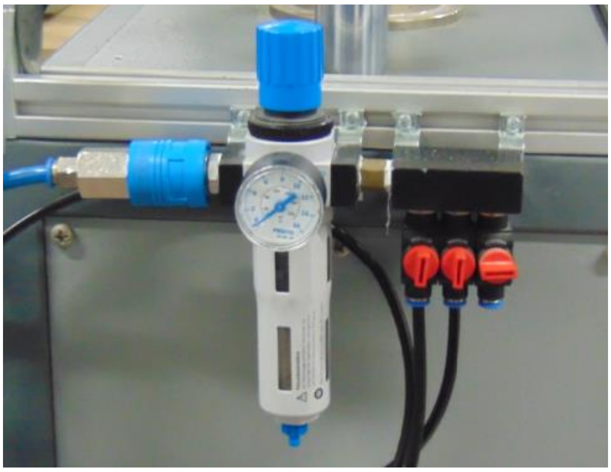

Figure A2.42: Air pressure set to 0

- We put the specimen in the superior jaw. The specimen must be in a position where it is held a bit over the bend radius. Remember that the off-valve must be active; blocking the jaw's fixing system.

  Fix manually the specimen, moving downwards the jaw's mechanism with your fingers (Figure A2.43).

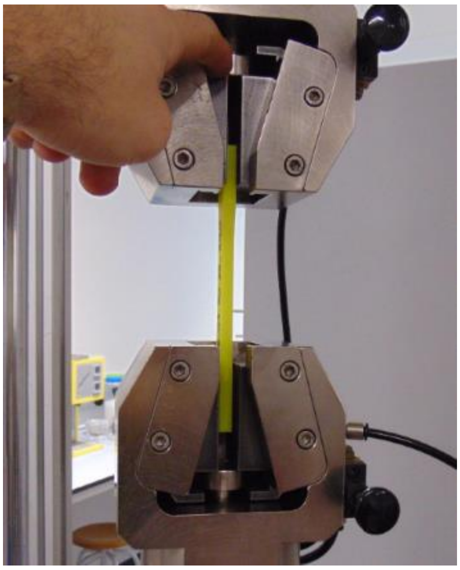

Figure A2.43: Manual fixation of the jaws

It is important not to fix it with much force because we will have to align it the best way we can so it stays totally vertical and parallel with the machine.

Now we should have our specimen fixed in the superior jaw and perfectly aligned with the machine, and the two jaw's blocking system off valves activated.

- Next we will apply pressurised air to the system. It must be a minimum quantity and we will stop giving more pressure to the system once we see that the lower jaw closes. Then, we will unblock the off-valve of the inferior jaw so that the lower part of the specimen is free again (Figure A2.44).

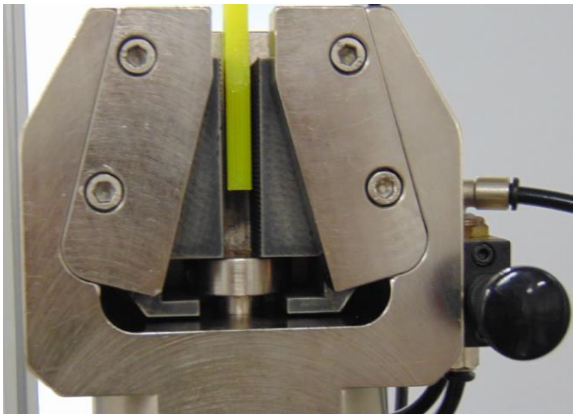

Figure A2.44: Application of minimal pressurized air

- Placing the extensometers.
  The extensometers must be placed in the parallel flat area of the specimen, vertically and well centred (Figure A2.45).
  Once installed, we will apply a bit of force to the middle zone (body) of the extensometer towards the specimen to avoid them to slide during the traction test.

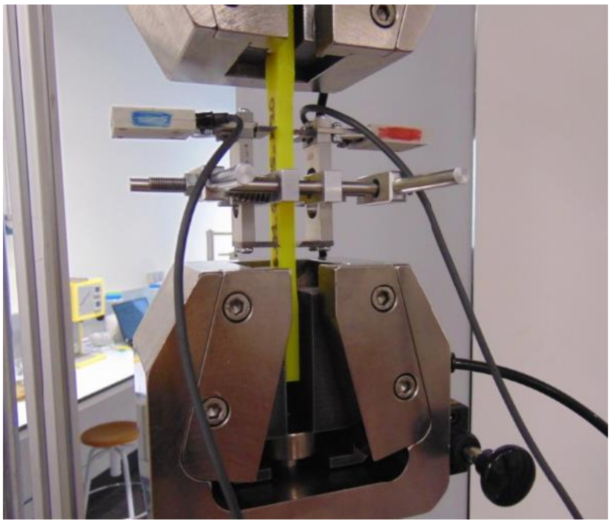

Figure A2.45: Extensometers placement

We will unblock the extensometers, being careful so that its cables don't touch the mobile parts of the machine so the extensometer razor (mobile part during the traction test) has total freedom of movement.

In the next image we can see from left to right how we go from having the extensometers blocked to them being unblocked by moving the safety metallic part so we can do the test (Figure A2.46).

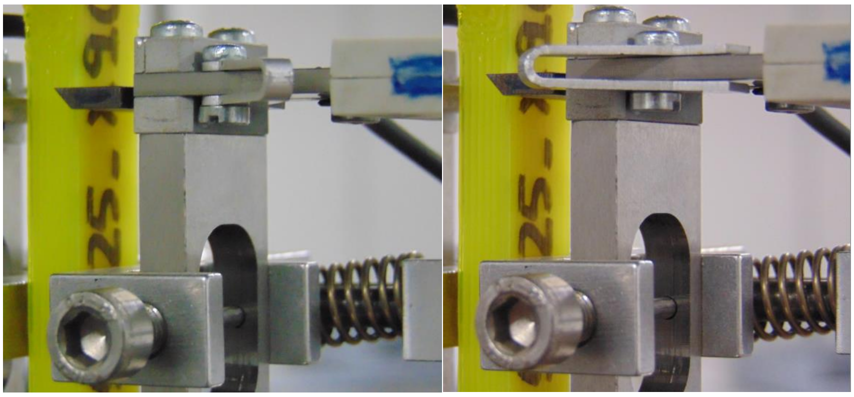

Figure A2.46: Unlocked extensometers

- Using the "Data Logger" software on the right computer (Figure A2.39) we will "Zero balance active channels" (Figure A2.47) and then we will run the data acquisition from the Spider program pressing "Start data acquisition" (Figure A2.48).

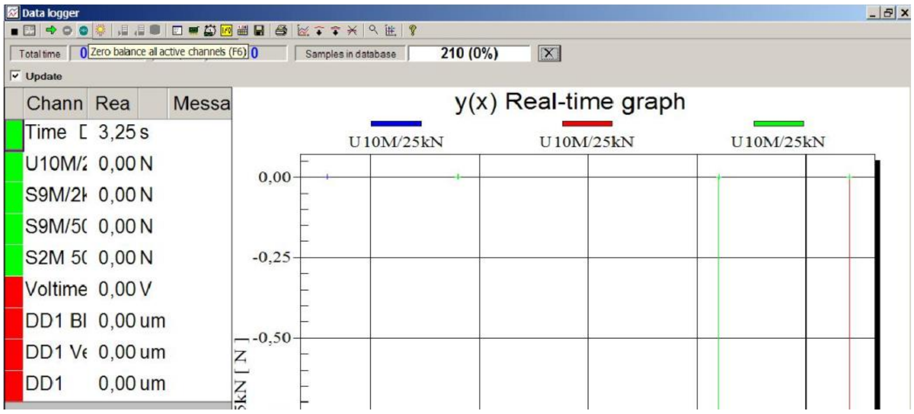

Figure A2.47: Zero balance active channels

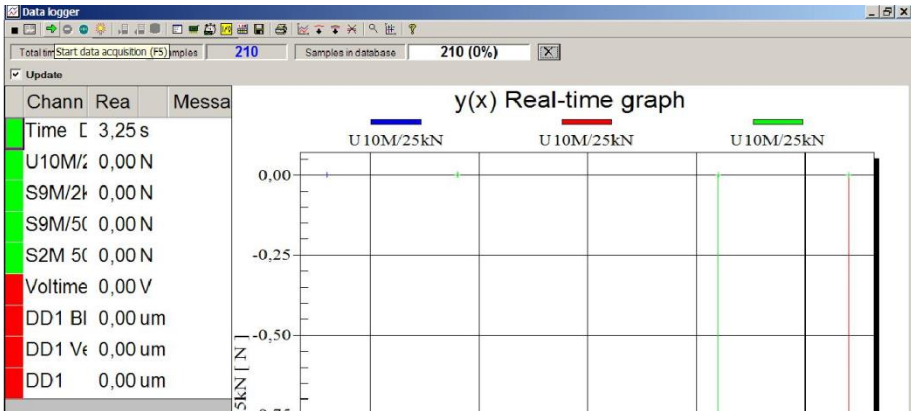

Figure A2.48: Start of data acquisition

- Using the "Microtest-Panel de Control" on the left computer (Figure A2.27) we will select "Autocero" (Figure A2.49) and then we will write down 50mm/min in the area where we can read the speed and the we will press the "Enter" key.

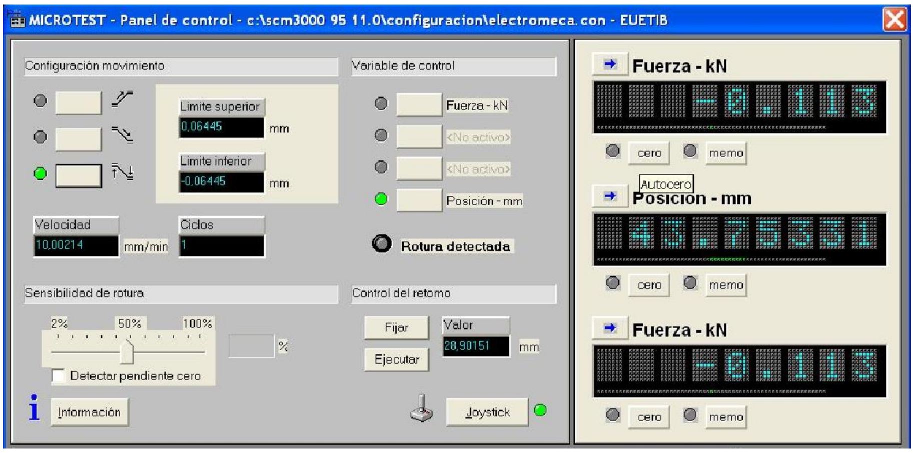

Figure A2.49: Autocero option selection

- With this configuration we will use the options from the control panel from the Microtest Joystick machine to close the inferior jaw to the point where we want to hold the specimen (a bit above the bend radius) (Figure A2.50).
  To activate the fixation of the inferior jaw we must activate the blocking valve pressing it (Figure A2.51).

Figure A2.50: Traction machine's control buttons

Figure A2.51: Jaw's lock button

- With the specimen fixated we return to the "Microtest-Panel de Control" software and we will select the "Autocero Posición". This way we are telling the software where our "zero" is before starting the test (Figure A2.52).

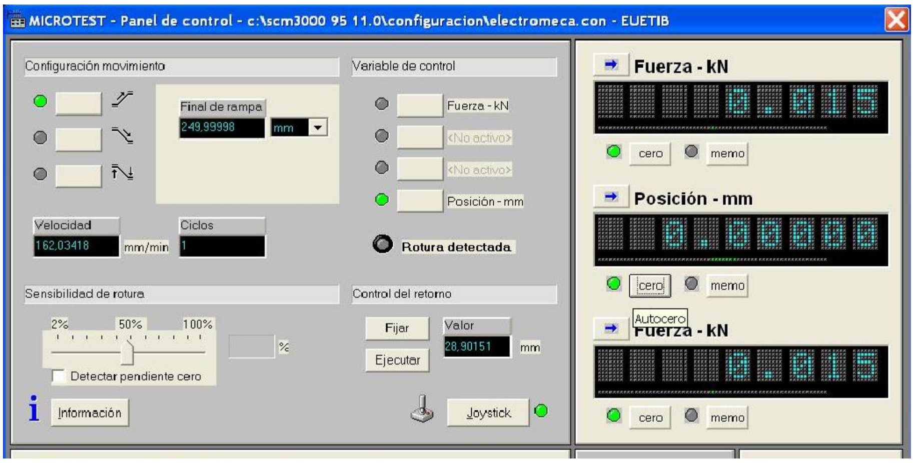

Figure A2.52: Selecting the Autocero option

This step will also allow us to adjust automatically the position of the inferior jaw in the next tests, because we have already our "zero" saved in the software.

If we want our lower jaw to place itself automatically in the fixing position we will have to follow the next steps in the "Panel de Control" software:

  - Write a 50mm/min speed value and press "Enter"
  - In "Configuration de Movimiento", click in the figure that shows the up direction.
  - In "Final de Rampa", as we have selected "Autocero Posición" previously, we will write the value "zero" and we will hit "Enter" to tell the software the point where we want our jaw.
  - We will select the engine by clicking on "Motor".
  - Lastly, we will select "Marcha". By doing this the machine will place the inferior jaw to the correct position where the specimen will be fixed.

- In the screen where we have the "Data Logger" software we can see that the force that the load-cell detects is not zero. This happens because we have fixated the specimen with the inferior jaw, and the jaw makes a bit of force upwards when it closes.

Moreover, we will have to apply more force to the jaw’s pneumatic system with the intention that the test must be done without any risk of the specimen moving or falling from the jaws.

With all this, an initial pre-charge will happen and we will have to counter it in order to make the traction test without wrong results.

Now we will explain how to suppress the pre-charge that the inferior jaw and the increase of pressure will apply to the system so that we can start the test with a “zero” force.

- We will go to the “Microtest-Panel de Control” software.
- We change the “Velocidad de Movimiento” value to 2mm/min and then we press “Enter” to confirm.
- We activate the Joystick option (Figure A2.53).

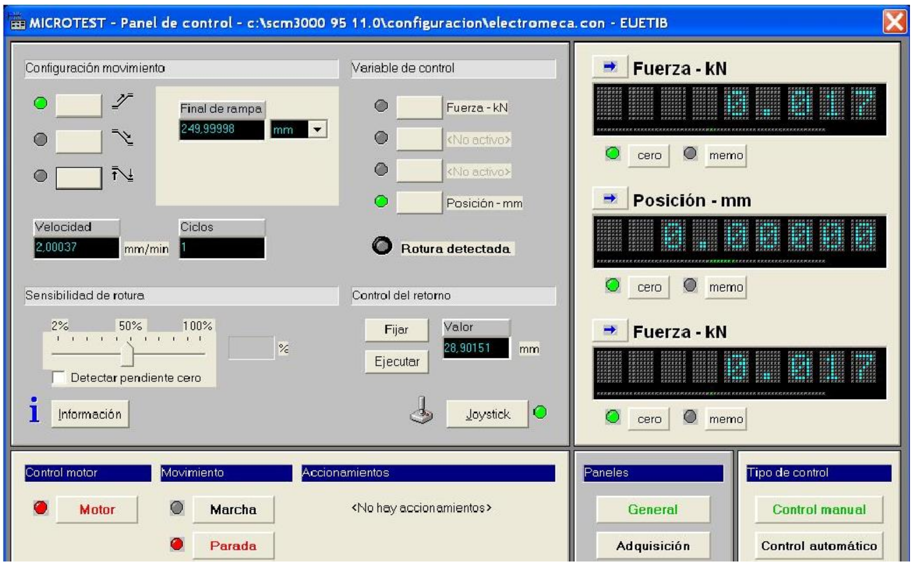

Figure A2.53: Joystick option activation

- To make zero the initial force we have to apply simultaneously pressurized air to the system (a maximum of 2 bar) and press the button that brings the inferior jaw downwards (in the machine control panel”) (Figure A2.54).

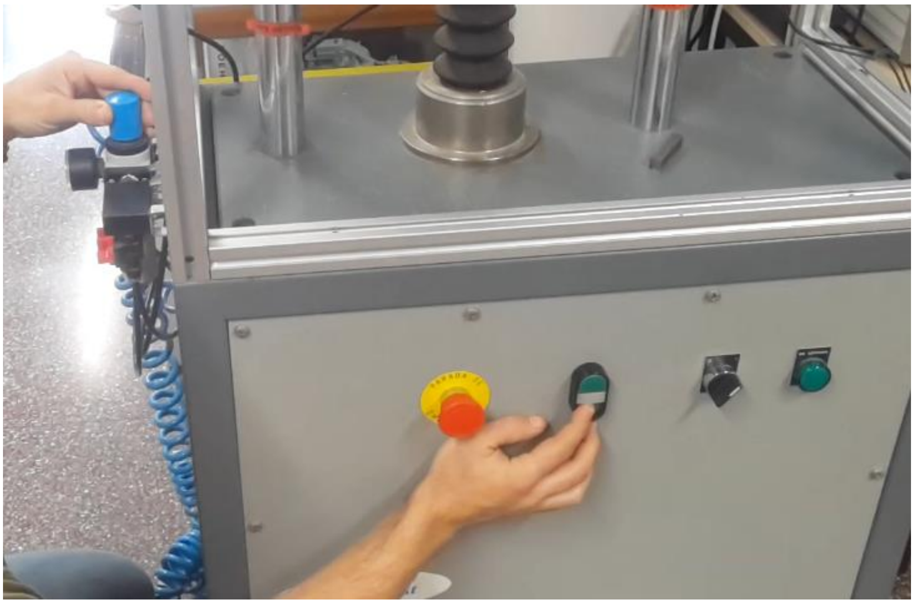

Figure A2.54: Making zero the initial force

In the “Data Logger” software screen we will see how when we augment the pressure that the jaws make to the specimen it suffers compression stress that must be suppressed. To do this we will apply a traction force to the specimen making the inferior jaw go down using the machine’s control panel joystick until we see in the screen we are reaching a zero force value while having a 2 bar pressure (Figure A2.55).
If we see that reaching the zero in the final moments of the process is being difficult we can change the speed value to 1mm/min to be more precise in the machine’s movement.

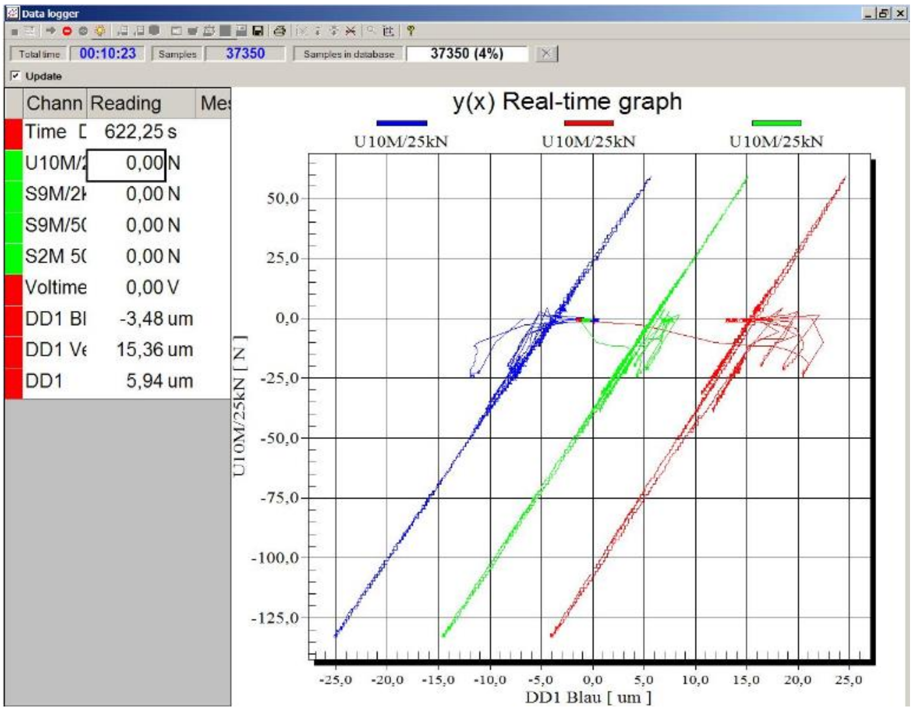

Figure A2.55: Reaching 0 force

- Test's parameters and execution.
    - 2 bar pressure
    - We go to the "Microtest-Panel de Control" software.
    - We change the speed value from 2mm/min to 1mm/min (if we haven't done it in the previous section) by writing the value in the speed area and pressing "Enter" (Figure A2.56)

Figure A2.56: Changing Velocidad (Speed) to 2 mm/s

- We click on the “Seguridad” button, and then on “Puntos de parada por alarma” we modify the “Fuerza maxima” option to 10kN and the “Fuerza minima” to 10kN. To do this we will write the value in their respective areas and we will press “enter” to confirm the changes (Figure A2.57).

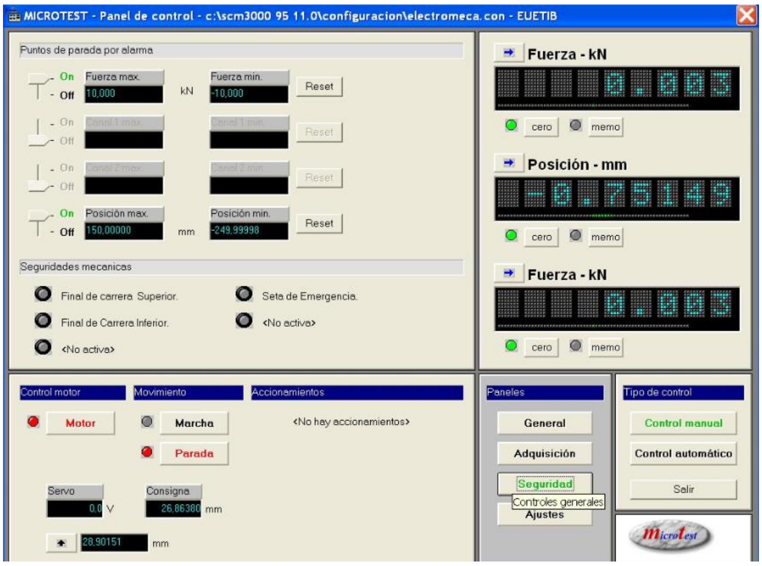

Figure A2.57: Selecting the last options before commencing the test

- We click on “Acquisition”, in the “Ensayo” area to modify the name of the test and we press “Enter” to confirm the changes (Figure A2.58)

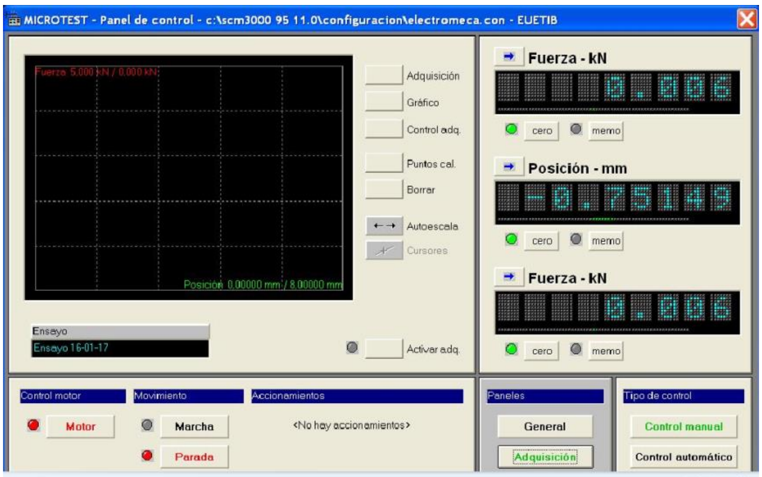

Figure A2.58: Starting the test

- In the same screen we press "Activar" (Figure A2.59).

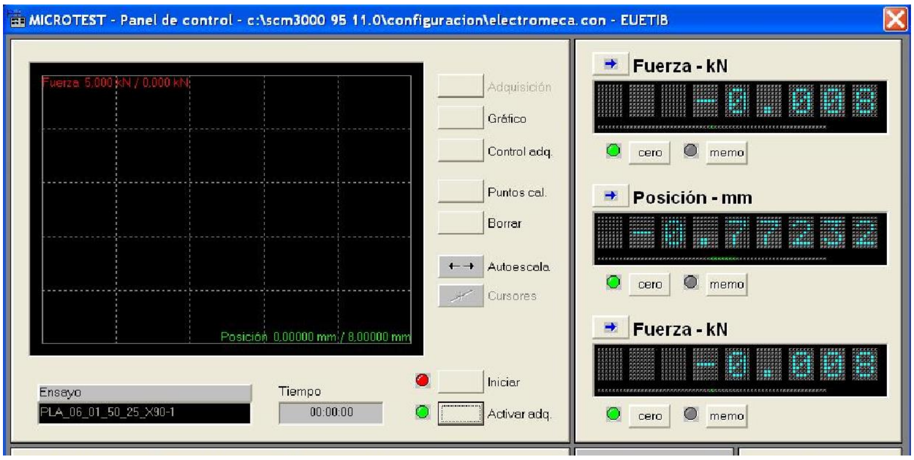

Figure A2.59: Activation option

- We press "Motor" (Figure A2.60).

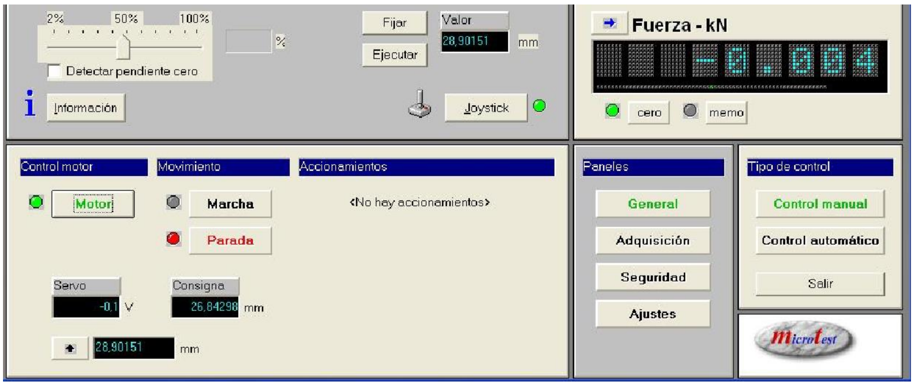

Figure A2.60: Activating motor option

- We go to the "Data Logger" software
- We stop the data acquisition by pressing "Stop data acquisition" (Figure A2.61).

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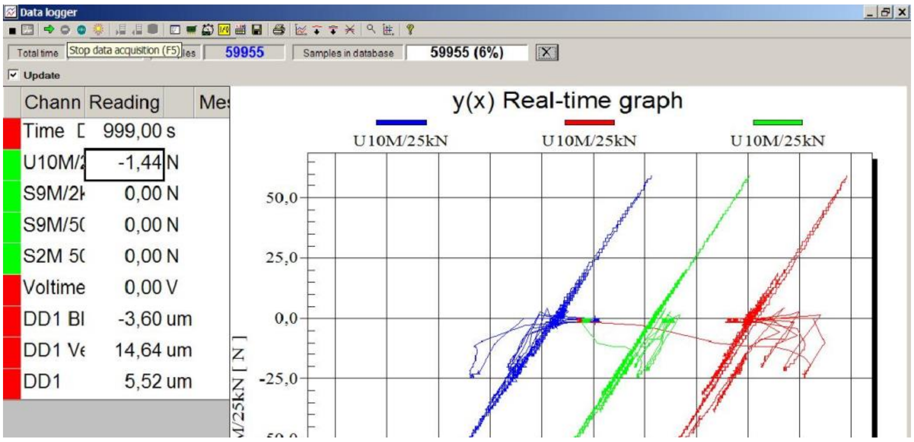


Figure A2.61: Stopping data acquisition

- We reactivate the data acquisition by selecting “Start data acquisition” (Figure A2.62).

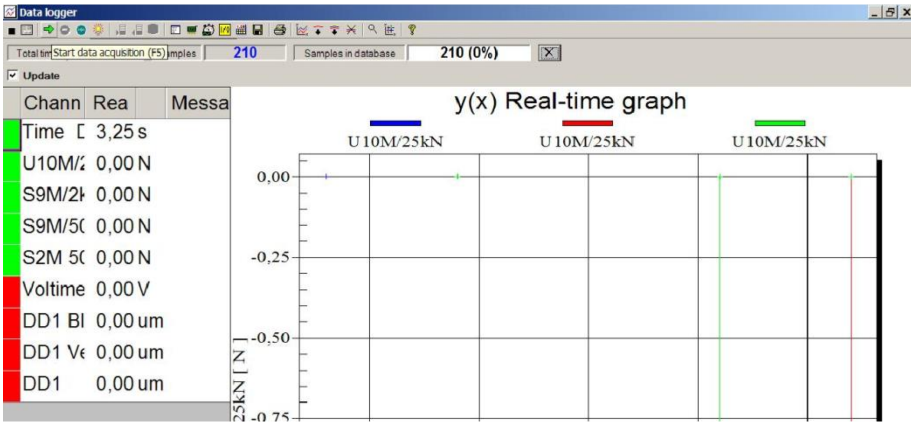


Figure A2.62: Starting data acquisition

- Immediately after we will go to the “Microtest-Panel de Control” software and we will start the test by selecting “Marcha” (Figure A2.63).

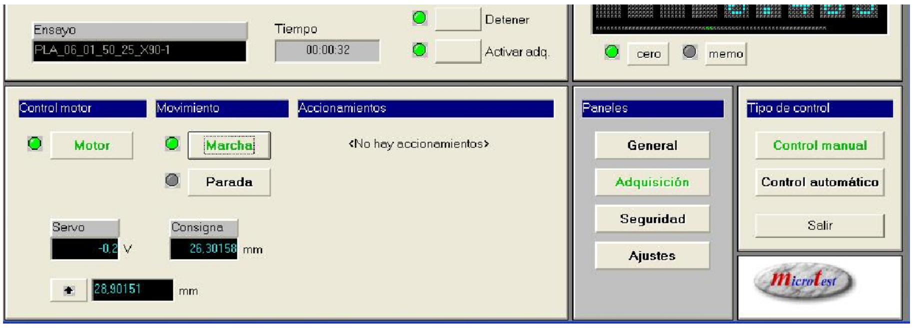


Figure A2.63: Selecting the Marcha (Start) option

- o The traction test should be in process (Figure A2.64).

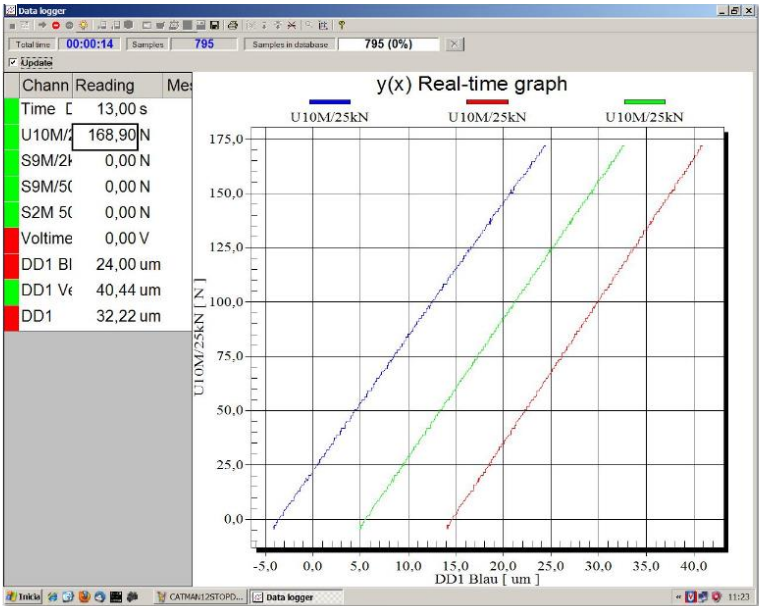


Figure A2.64: Traction test

- Test's ending.
  - o When de specimen breaks, we will click on the "Stop Data Acquisition" button on the "Data Logger" window (Figure A2.65). Next, we will go to the "Microtest-Panel de control" software and we will hit "Parada"; this will end the test (Figure A2.66). All this have to be done quickly. This will prevent us to acquire useless data at the end of the test.

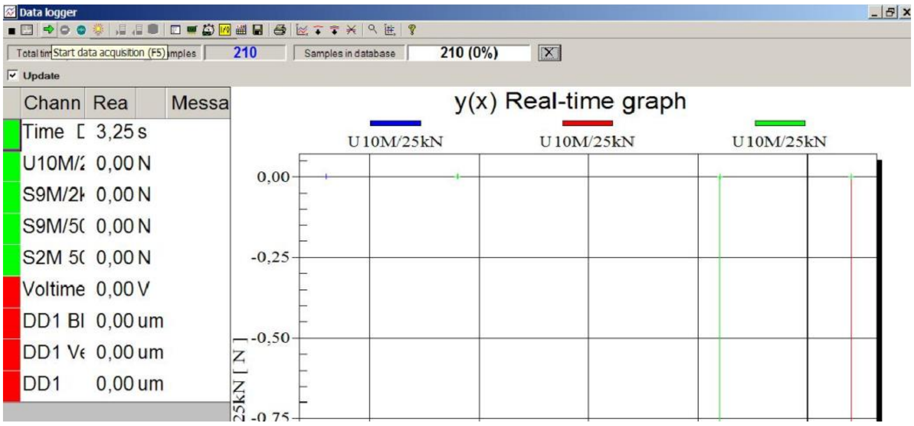


Figure A2.65: Stopping data acquisition

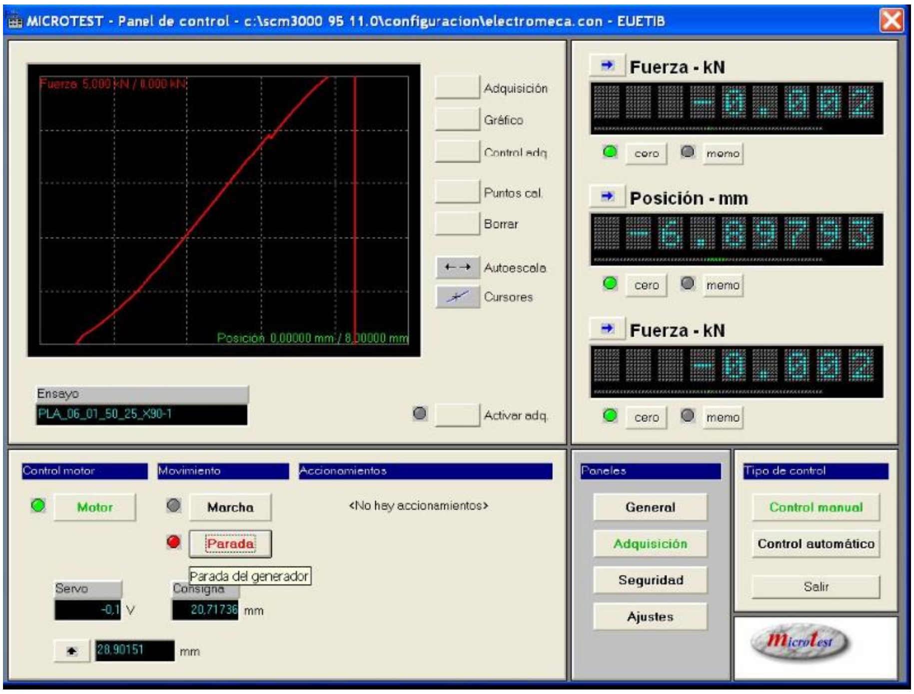


Figure A2.66: Test's end

- Next, we will take off the extensometer- When we are not working with the extensometer we should put something between the blade and fix them. This is the proper way of taking care of this tool (Figure A2.67).

Figure A2.67: Taking care of the extensometer when not working with it

- We will get the 2 (or more) separate parts of the specimen that are still fixed to the machine. To do this we will unlock the pressure valves from the jaws pulling them, always being careful and remembering that the pneumatic system is still active (Figure A2.68).

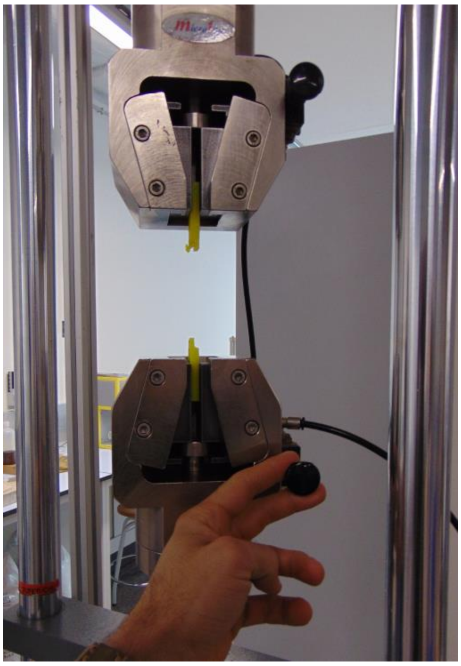


Figure A2.68: Unlocking the jaws

- Next we we will reduce the pressure to a minimum via the pressure control system and we will use the air hand nozzle to clean the little remainings of the specimen that may have been broken during the test. This allows us to have a clean working space to properly test the next specimens (Figure A2.69).

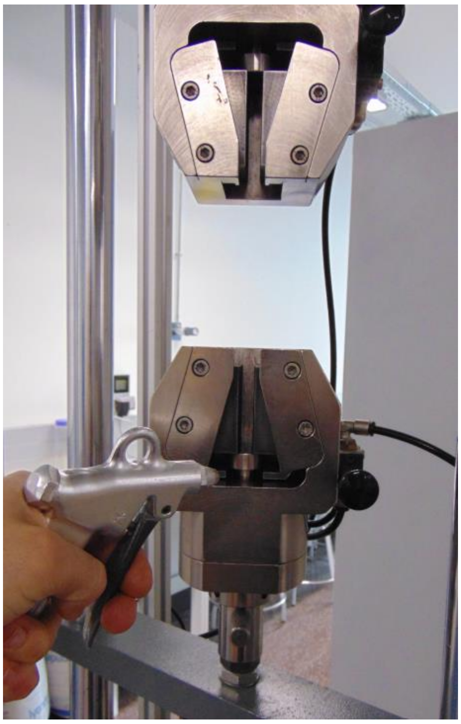


Figure A2.69: Cleaning the working area after the test

- Data storage.
  - In the "Data Logger" software, select the save button (the one with a floppy disk image) (Figure A2.70).

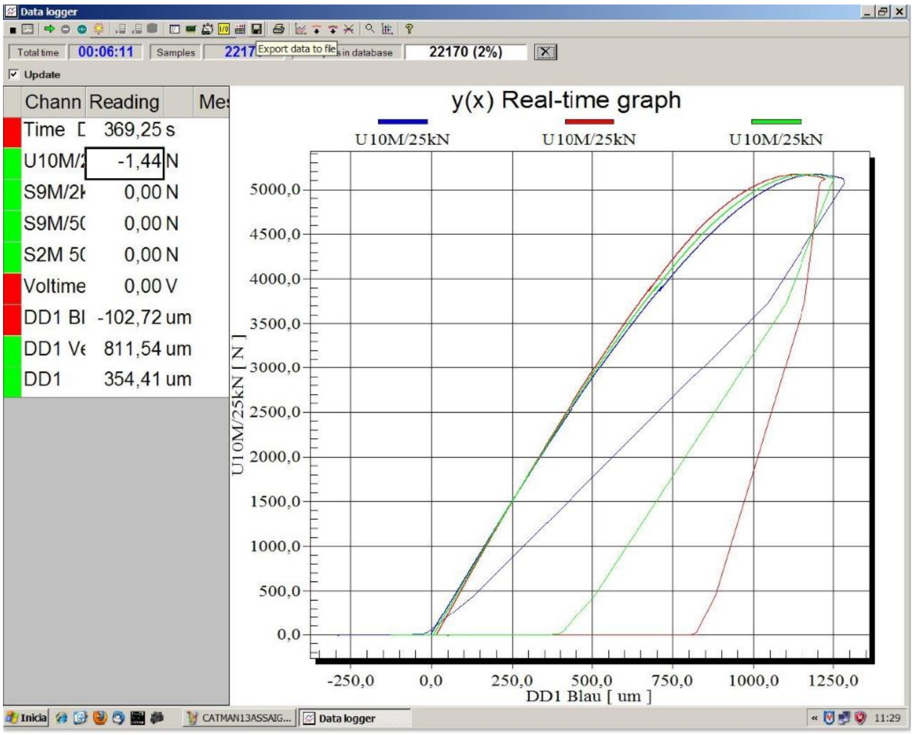


Figure A2.70: Selecting the save button

- It will appear the emerging window "Data Export". On the right we will select "ASCII + Channel Information", on the middle menu "Channels to be exported" we will select the information that we want: "Time Device_1", "U10M/25kN", "DD1 Blau", "DD1 Vermell" and "DD1" (Figure A2.71).

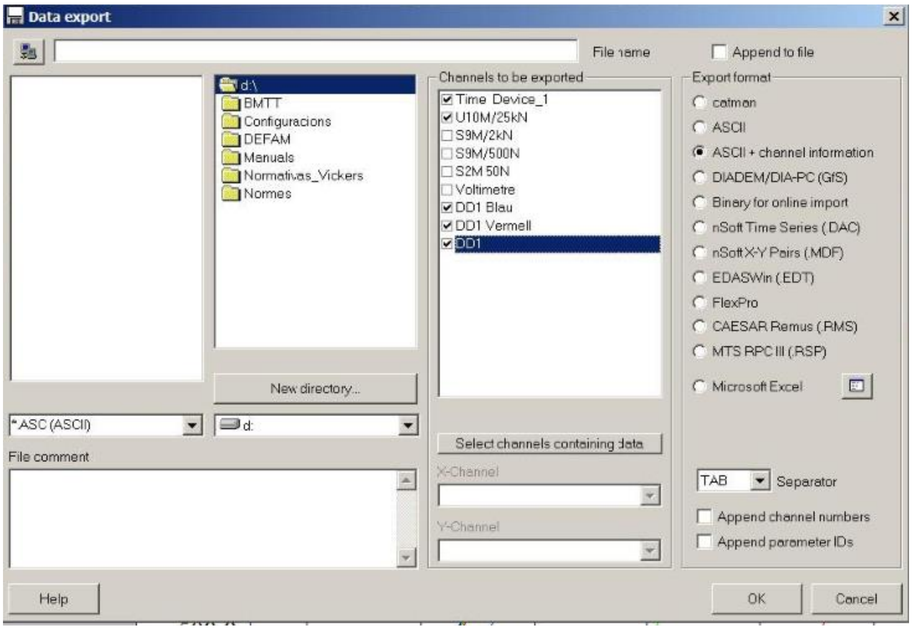


Figure A2.71: Selecting the channels that we want to save

- We click on unit “D”, “DEFAM” and the button “New Directory”, we create a folder with our name. When we have our folder selected (double click) we can create a new one inside this one by clicking again on “New Directory” and we can give it its appropriate name (Figure A2.72).

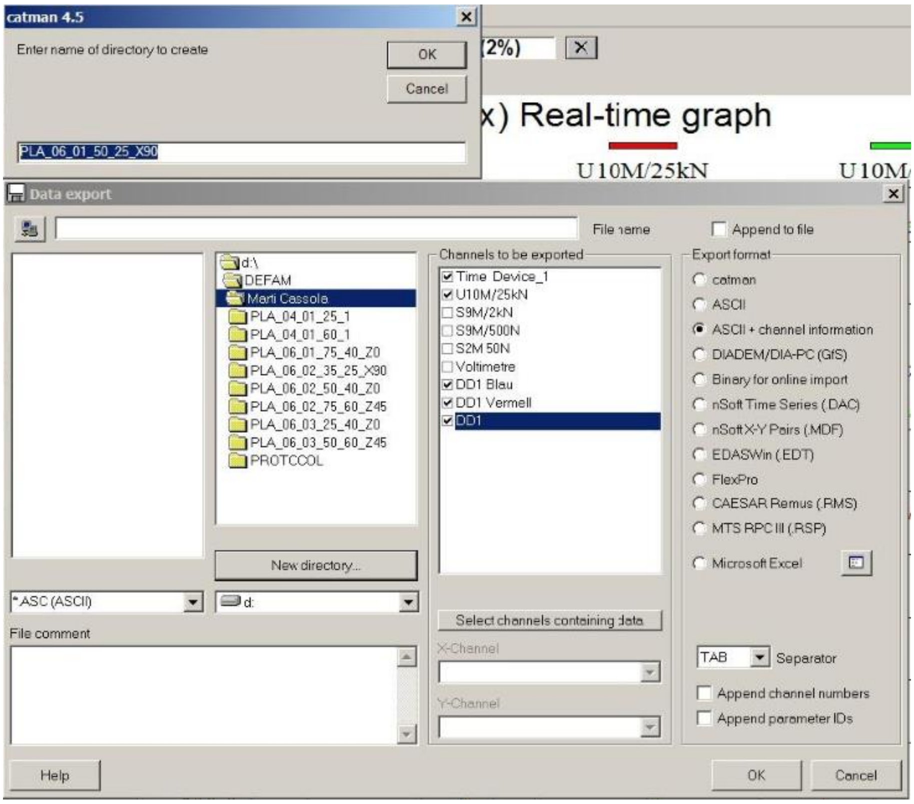


Figure A2.72: Creating a new directory for the data storage

- Lastly we save our folder’s name in the box “File name” and we click “Ok”, this way, we will save our tests in an organized and rigorous way (Figure A2.73).
  With this we would have completed our ABS specimens test.
  To do another test we would have to follow again this procedure in a rigorous way so that we can carry out our tests in a satisfactory way.

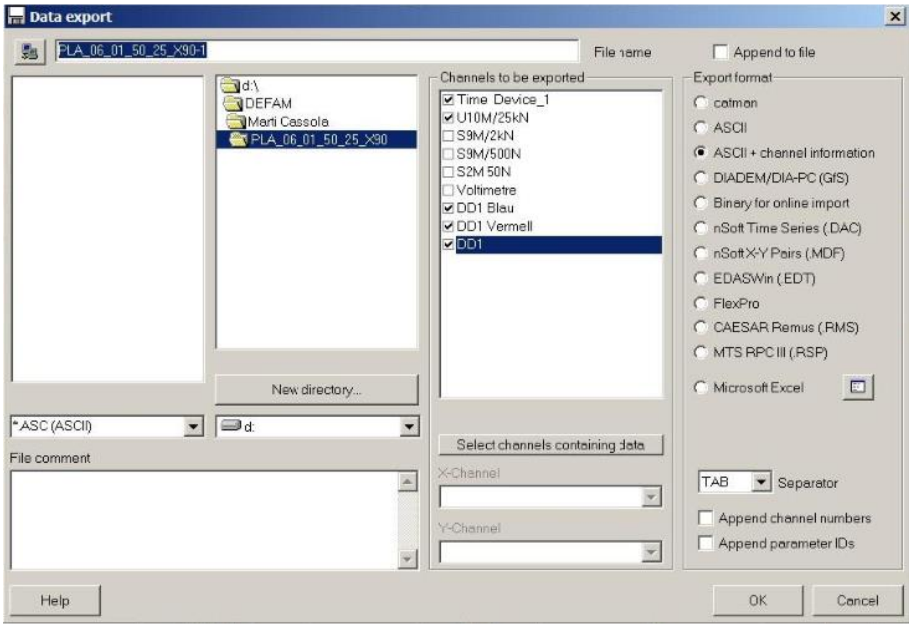


Figure A2.73: Saving the tests

10.8. Disassembly

The disassembly process is divided in two blocks, the first one concerns the electronic part (wires, software) while the second one concerns the mechanical elements of the traction machine (jaws, pneumatic system, power cell).

- Electronic part:
  - Disable the traction machine rotating the control panel's black button to the "0" position (Figure A2.29).
  - Close the Microtest and Data Logger software.
  - Unwire and withdraw the DS/MS cable from the 25 kN power cell (Figure A2.22).
  - Disconnect and withdraw the extensometers, making sure that they are locked (Figure A2.46).
  - Disconnect and withdraw the LPT cable that connects the computer (printer port) on the right with the Spider (PC port) data acquisition software (Figure A2.10).
  - Turn off the Spider data acquisition module pressing the ON/OFF switch on the back of the module.
  - Disconnect the power supply in the PS/2 cable. This cable connects the "V DC IN" port from the Spider system with the electric system (Figure A2.9).
  - Disconnect and withdraw the PS/2 cable (Figure A2.8)
  - Turn off the computers.

Every one of the components will be saved and stored very carefully on its own receptacle, this way we will make sure that each part is in good conditions to be used in other occasions.

- Mechanical part:
    - First we have to make sure that the pressure system is off, which means that there is no pressure, this way we will avoid the jaws to activate on accident during their manipulation when we are doing the disassembly.
      The pressure valve must be closed and the pressure indicator must be on “0” bar. Next, we will disconnect the tube that supply pressurized air to the jaws (Figure A2.14).
    - Unscrew the inferior screw that fixates the inferior jaw with the machine’s frame, using the 20-22 open end wrench and the 24-27 ring spanner (Figure A2.31).
    - Withdraw the pin that unites the previous group.
    - Withdraw the inferior jaw.
    - Unscrew the inferior screw that unites the superior jaw with the 25 kN power cell coupler using the 35-50 spanner wrench and the 24-27 ring spanner (Figure A2.20).
    - Withdraw the pin that unites the previous group.
    - Withdraw the superior jaw.
    - Withdraw the coupler that we put in the power cell using the 35-50 spanner wrench and the 80-120 ring spanner (Figure A2.19).
    - Unscrew the power cell from the strength transductor using the 80-120 spanner wrench and the 20-22 open end wrench (Figure A2.18).

The disassembly has been correctly done.

11. Annex 3: Excel functioning and basic theory

This section explains how the calculus of the output parameters are made (Young modulus, elastic limit, maximum tension, maximum elongation, resilience modulus and tenacity modulus), using the data taken from the traction tests.

To do this, a Standard Excel sheet has been created. Every sheet is designed to calculate the different parameters that characterize the properties of the used material. In this case, ABS.

The results will vary depending on the behaviour stress-strain of the material that is associated with the configuration of the manufacturing parameters that form the specimen. Because the number of tests is high, the process will be explained for one of the specimens. The example specimen is one of the ones printed with the configuration number 10 of the Taguchi's orthogonal arrangement; its name is "ABS_04_01_25_40_X90_TRAC_1".

11.1. Metrology

In order for the experiment to be exhaustive, a rigorous control of the data has to be followed during the process. For this reason, the first step consists on creating an adequate naming structure to the necessities of the experiment, it has to be clear, specific and easy to identify (figure A3.1).

In this case we have opted to name the specimens using their own manufacturing parameters, the ones that intervene in the specimens properties: the first block refers to the material used in the manufacturing (ABS); the second informs us of the levels of every manufacturing parameter used to print the part; the third one references to the kind of test which the specimen has been under (TRACtion); the fourth and last tells which of the 5 specimens with the same properties we are working on (1).

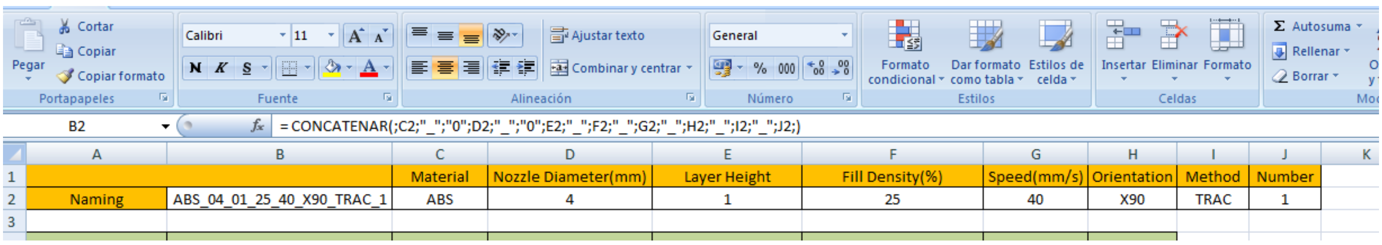


Figure A3.1: Naming of the Taguchi configurations

Previous to the beginning of the test. All the specimens have been measured (thickness and width) in different sections along their central part in order to calculate the section. The weight of every specimen has also been noted in the excel sheets.

All the results taken with instruments are not mathematically exact because all of the tools used for measurement have their own precision. This means that the final result of a measurement will be formed by a result that comes from a group of measurements. This result will have an error. The total error (Etot) of a measurement will always be the sum of the following errors:

$$Etot = Eres + Eacc$$

1. The resolution error is limited to the precision of the measurement tool. In this case the measurement tool used for the thickness (h) and width (b) measurements of the specimens is a digital micrometer with a maximum precision of 0,001mm.

$$Eres(h) = 0.001mm$$
$$Eres(b) = 0.001mm$$

   The resolution error for an indirect measurement has to be evaluated through the other measurements that can be measured. In this project the indirect measure is the section of the part (a) that depends of the thickness and width.

$$Eres(A) = \left|\frac{\partial A}{\partial h}\right| Eres(h) + \left|\frac{\partial A}{\partial b}\right| Eres(b)$$

2. The accidental error accurs when different measurements of the same apparent magnitude in the same conditions give different values. Its estimation is based on statistical methods.
   For direct measures (h, b) the next formulas are used, where N is the number of measurements, tp(N-1) is deduced using the Student Distribution with a hope interval of 95%, S is the Standard deviation.

$$Eacc(h) = tp(N-1) * \frac{S}{\sqrt{N}}$$

$$S(h) = \sqrt{\frac{1}{N-1} * \sum_{i=1}^{N} (hi - \bar{h})^2}\ \bar{h} = \frac{1}{N} * \sum_{i=1}^{N} hi$$

$$Eacc(b) = tp(N-1) * \frac{S}{\sqrt{N}}$$

$$S(b) = \sqrt{\frac{1}{N-1} * \sum_{i=1}^{N} (bi - \bar{b})^2}\ \bar{b} = \frac{1}{N} * \sum_{i=1}^{N} bi$$

   On the other hand, for the indirect measures (A) we use:

$$Eacc(A) = \sqrt{\left[\frac{\partial A}{\partial h} * Eacc(h)\right]^2 + \left[\frac{\partial A}{\partial b} * Eacc(b)\right]^2}$$

Sizing (mm)	h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	Eres(h)(mm)	h' (mm)	S(h) (mm)	Eacc h (mm	Err(h) (mm)
	7,173	7,156	7,165	7,164	7,171	0,001	7,166	0,007	0,006	0,007
	b1 (mm)	b2 (mm)	b3 (mm)	b4 (mm)	b5 (mm)	Eres(b) (mm)	b' (mm)	S(b) (mm)	Eacc b(mm	Err(b) (mm)
	13,9	13,795	13,825	13,836	13,854	0,001	13,842	0,039	0,037	0,038
Cross Area (mm^2)	A1 (mm^2)	A2 (mm^2)	A3 (mm^2)	A4 (mm^2)	A5 (mm^2)	Eres(A) (mm)	A'(mm^2)	S(A) (mm)	acc A (mm	Err(A) (mm)
	99,705	98,717	99,056	99,121	99,347	0,021	99,189	0,293	0,280	0,301
Weight	13,914	N	5	tp(N-1) 95%	2,13					

Figure A3.2: Width, thickness and weight data plus error calculations from the part "ABS_04_01_25_40_X90_TRAC_1"

11.2. Stress-Strain curve

The data file containing the force and lengthening obtained through the traction tests thanks to the Spider data acquisition system makes it possible to calculate the Stress-Strain curve from the specimens

To show the independent terms of the specimen size, the loads (applied forces), will be divided by the original transversal section (A) this way obtaining the traction resistance.

$$\sigma(MPa) = \frac{F}{A}$$

On the other hand, while running the test, the length of the specimen will increment, the deformation will have to be measured taking into account the length that it has at every moment of the test. The deformation will be calculated as:

$$e = \frac{L - L_0}{L_0}$$

L references the length of the specimen in every moment calculated through the mean of the two extensometers while L_0 represents the initial length of the specimen, 50mm.

The data gathered using these magnitudes will allow us to create the characteristic curve of the material of each of the specimens and this way be able to see the properties of this kind of curves (Figure A3.3).

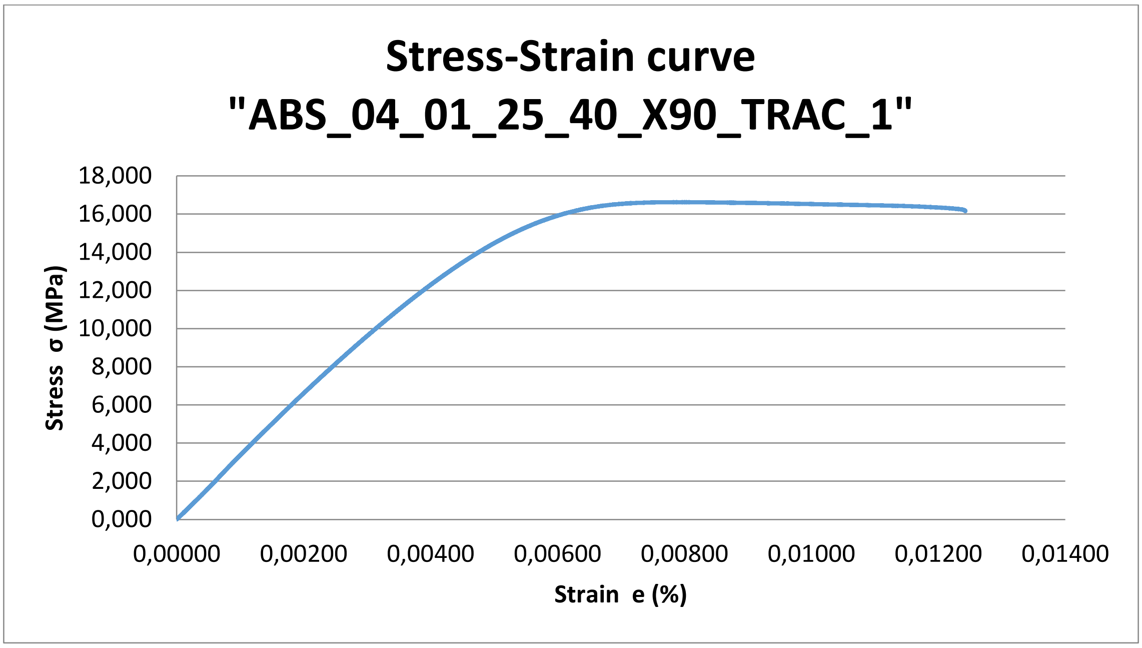


Figure A3.3: Stress-Strain curve from the "ABS_04_01_25_40_X90_TRAC_1" specimen

In annex 1 (A1) all the Stress-Strain curves for all the mean curves of the graphs can be found

11.3. Output parameters

Thanks to the data that forms the Stress-Strain curve, different properties of the tested material can be determined. Some of these properties are called output parameters or out-parameters and they have been obtained using the graphic representation of the traction test or calculating them.

The parameters we are talking about are the following:

- Young Module o Proportional limit.
- 0,2% Offset Yield Strength.
- Ultimate Tensile Strength.
- Maximum Deformation.
- Resilience module.
- Tenacity module.

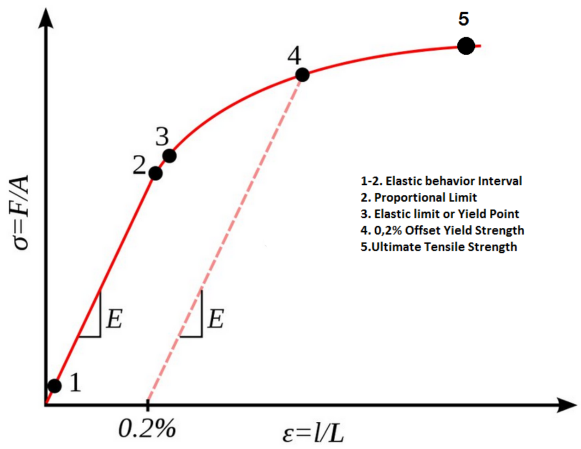


Figure A3.4: (2016). Properties on a Stress-Strain curve (Figure). Recovered from http://www.cadimensions.com

11.3.1. Young Module, E (GPa)

In the first part of the test (interval 1-2 of the figure A3.4.) it exists a linear relation between the applied tension and the deformation. This proportionality coefficient between the tension and the deformation is called Elastic Module or Young Module and it is characteristic of the material. This section known as elastic zone is where the rest tube performs as a spring: if the load stops applying force the specimen will return to its original length. The elastic zone is represented by the next formula:

$$\sigma = Ee$$

where σ represents the effort the effort that the transversal section suffers due to the applied load, E is the Young module and e is the deformation.

The graphic representation of the equation in this section, is in fact a straight line, where the inclination of the line E is defined by the quotient between the tension and the deformation, and the independent term (b) represents the point where the line cuts the y axis (σ).

$$y(x) = ax + b$$
$$\sigma(e) = Ee + b$$
$$E = \frac{\sigma}{e}$$

So to get the ideal value of the Young modulus for each of the specimens tested the interval where the group of experimental dots (e,σ)adjusts better to the line has to be found. This would be an easy task if it were not because in reality we will never find that the dots fit a perfect straight line, they are a little disperse. For this reason, we will look for a method to find the line that adjusts better to this group of dots, this way we will be able to obtain the inclination of the line and it will be possible to find the characteristic Young Module for the tested specimen (Figure A3.5).

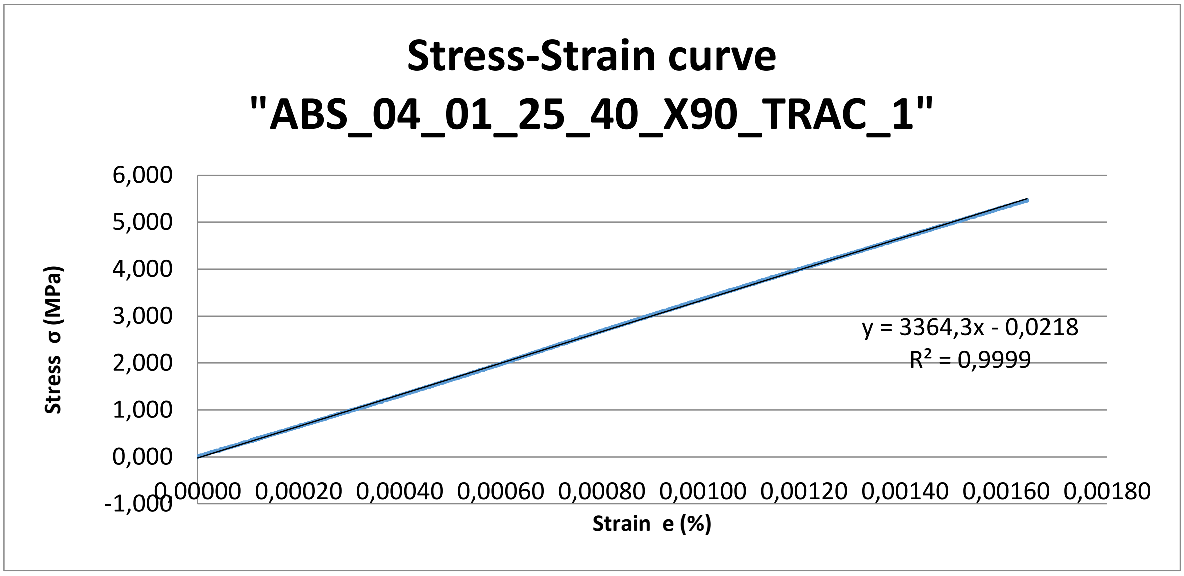


Figure A3.5: Section from the graph with the minimum linear regression error

The method consists on elaborating some iterative processes that will be carried out by the Excel software that adjust the optimal interval between two dots. Every iterative loop will be calculated between two extremes previously defined by the previous iteration. During the first iteration, as we have all the data available to us, we will use the interval between the starting value and the maximum tension also known as the Ultimate Tensile Strength of each specimen.
After that, every iteration determines which is the group of data that conforms the regression line with the minimum error of the (a) parameter or Young Module, as well as the Young Module's value in the interval of the data that being calculated.

At the same time the iteration indicates which is the point where the minimum error is found, and it is used to identify the extreme that will have to be taken into account for the next iteration. This process will be successively repeated for the next iterations taking care of changing the direction and the interval where the iteration has to be executed.

When the error value and the module match for three successive iterations, the defined starting and ending point for these iterations will form the two points of the optimal interval and thus the module value will be accepted as correct.

To calculate the minimum error attributed to the estimation of the (a) parameter and the Young Module, each iteration does another repetitive process that starts calculating the dispersion of the line between three dots (minimum number of experimental dots so that the calculus makes sense),

next another dot will be added to do again the same operation and keep repeating the process until reaching the last dot where the iteration interval ends.
The dispersions of the line for each of the dots is defined by the next formula:

$$f(a,b) = \sum_{i=1}^{N} [(axi + b) - yi]^2$$

The excel script looks for the line $[y(x) = ax + b]$ finding the coefficients (a,b) resolving the previous equation by the squared minimum criteria, where the solution is the next:

$$a = \frac{\sum_{i=1}^{N}(xiyi) - N\bar{x}\bar{y}}{\sum_{i=1}^{N}(xi - \bar{x})^2} \qquad b = \bar{y} - a\bar{x}$$

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} xi \qquad \bar{y} = \frac{1}{N}\sum_{i=1}^{N} yi$$

Once the software gets the coefficients that determine the line, it calculates the (a) parameter for each group of dots that is being evaluated, using the following equation:

$$Eacc(a) = tp(N-2)\frac{A}{\sqrt{N-2}} \qquad A = \sqrt{\frac{f(a,b)}{\sum_{i=1}^{N}(xi - \bar{x})^2}}$$

Once that all the errors associated to the Young Module parameter has been evaluated for each one of the lines of every iterative process, the one that has the minimum error is chosen.

Finally, the spot where the last data that forms the regression line with the minimum error will have to be registered, because it will register the extreme for the next interval in the iteration that follows.

All this process will be done for every iteration but it will have to be interleaving the direction of the calculus for each iteration, this way the optimal interval is adjusted (Figure A3.6).

0,021	99,189	0,293	0,280	0,301					
				E (MPa)					
				3364,31345	3364,313	3364,313	3364,313	3364,313	3364,313
				Error	Error	Error	Error	Error	Error
			Extrem	0,000179435	0,000179	0,000179	0,000179	0,000179	0,000179
		Inici	1		1		1		1
		Final	12840	3492		3492		3492	
e (%)	σ (MPa)								
0,00000	0,000				0,000179		0,000179		
0,00000	0,015				0,00018				
0,00000	0,015			0,34641016	0,00018				
0,00001	0,029			0,14142147	0,00018				

Figure A3.6: Iterative process to find the Young Module out-parameter

11.3.2. 0,2% Offset Yield Strength, σ_y (MPa)

The elastic limit (Yield Strength) is the maximum tension that a material is able to accept without having permanent deformation, meaning that if tensions bigger than the ones of the limit are applied the material will experience a plastic behaviour with permanent deformations and it will not spontaneously recover its original shape when the load isn't applied anymore.

Due to the difficulty of finding exactly where this point is, in engineering a conventional criterion is adopted where it is considered as Yield Strength the tension where the material has a plastic deformation of the 0.2% or e=0.002.

To determine the tension in this point (σ_y), the following process has been followed:

1) The line equation is defined for a 0.2% deformation.

$$\sigma_y = Ee + \sigma'$$

Because the elastic limit is still found in an elastic zone, it means that it shares the same inclination in this section with the previously calculated. For this reason, the line is moved from the optimal interval to the right multiplying by (-0.002), creating the 0.2% straight line. The axis intersection function determines the independent term or the cross point (σ') with the x axis of this line, doing the next operation:
The equation that defines the elastic zone complies:

$$\sigma = Ee + \sigma_0$$

Which means,

$$\sigma = Ee + \sigma_0$$
$$\sigma = E(e - e_0) + \sigma_0$$
$$\sigma = E(0 - e_0) + \sigma_0$$

The independent term of the equation that determines the line for a 0,2 deformation is,

$$\sigma' = \sigma_0 - eE$$
$$\sigma_y = Ee + \sigma'$$

2) The minimum distance between the data that forms the Stress-Strain of the traction test and the Yield Strength to the 0.2% defined in the section number 1 is calculated.

3) The minimum value would be the closer one, meaning that it would be the 0.2% yield point between the elastic limit line and the graph of measured data.
But because the data has so much noise, the one closer doesn't have to be the better one.
For this reason, what it is done is to calculate a regression line of the data measured around this point. This will be named local adjust.
The number of data that will be used to the right and to the left of this point has been set to 30 for each side.
The reason of this value is that it has been proved that a lower value will make it noisier while a higher value will make the adjusting area to stop being a line and this will also be bad.
The equation of the line that determines this local adjust is:
$$\sigma_y = me + \sigma''$$
Where (m) is the inclination of the line of the local adjust and (σ'') is the cross point between the adjusted local line with the x axis (σ).

4) Calculus of the 0.2% Yield Strength.
We will isolate the deformation of the equation of the local adjust, of which we already have the values for the inclination (m) and the independent term (σ'').
We will replace this equation with the one that that determines the tension of the 0,2% Yield point to obtain the final value (and more accurate) of the 0,2 Yield Strength tension.

$$\sigma_y = me + \sigma'' \qquad e = \frac{\sigma_y - \sigma''}{m}$$

$$\sigma_y = Ee + \sigma'$$

The final result of the substitution is the 0,2% Yield Strength for each experiment.

$$\sigma_y = \frac{(m\sigma' - E\sigma'')}{m - E}$$

11.3.3. Ultimate Tensile Strength, σ_{max}(MPa)

This tension represents the material's traction resistance, in other words, the maximum load that that the specimen can take divided by its initial section.

This point is the maximum traction tension that the specimen must suffer while the test is running.

To find this value the maximum F/A relation has to be found using the data gotten during the test.

11.3.4. Maximum deformation, e_{max}

The maximum deformation in this project refers to the one in the breaking point of the specimen, meaning the maximum lengthening of the specimen when the test has finished.

This value corresponds to the last value registered by the acquisition data system when the specimen breaks.

11.3.5. Resilience module, MR (MPa)

The resilience is a material's capacity to absorb elastic energy while it is deforming and giving it away when the load is lifted. The associated property is called Resilience Module, MR, which is the deformation energy by volume unit that it is required to deform a material until reaching the elastic limit or Yield Point.

Because we have the Stress-Strain curve, the resilience module of the specimen under an axial load is exactly the area until the fluency point (Figure A3.7.).

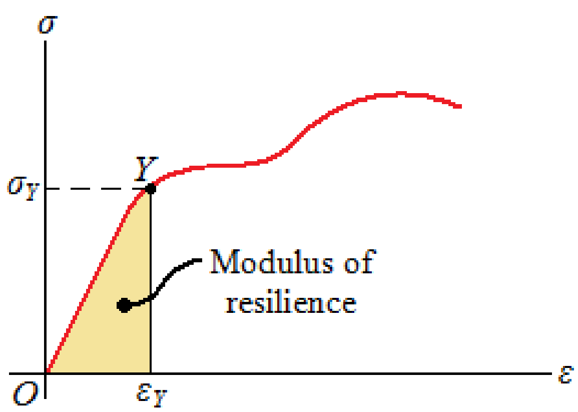


Figure A3.7: (2016) Resilience Module (Figure). Recovered from http://www.cadimensions.com

Guessing that the lineal elastic region (σ=Ee) we have:

$$MR = \int_0^{e_y} \sigma de$$

$$MR = \frac{1}{2}\sigma_Y e_Y \text{ (àrea del triangle)}$$

To determine the area of the triangle that is closer to the linear function, the area has been divided in little interval limited between a point (e_i, σ_i) and the next one (e_{i+1}, σ_{i+1}) of the data that form the curve until reaching the last interval established by the elastic limit (e_y, σ_y). Each of the intervals forms an area under the curve formed by a triangle and a rectangle that is calculated using the following formula:

$$A = \frac{1}{2}[(\sigma_{i+1} - \sigma_i)(e_{i+1} - e_i)] + [(e_{i+1} - e_i)(\sigma_i)]$$

$$A = \frac{1}{2}[(\sigma_i + \sigma_{i+1})(e_{i+1} - e_i)]$$

The sum of each of these areas becomes the total value of the shaded area, which is the resilience module, MR.

11.3.6. Tenacity module, MT (MPa)

The deformation energy result of the part breaking is called Tenacity module. The energy per volume unit required to cause rupture in a material is related with its ductility and resistance (Figure A3.8).

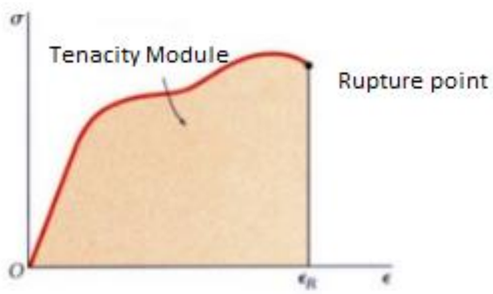


Figure A3.8: (2016) Tenacity module (Figure). Recovered from http://www.cadimensions.com

Finally, this calculation has been made like the one from the Resilience module, by adding all the little sections we have divided that are under the Stress-Strain curve. This value will always be bigger than the one from the Resilience module.

12.Annex 4: 3D printer specifications

Because the printer is a basic component of all the experiment it is important to talk about it and its characteristics. Not all the 3D printers are the same and have the same printing quality so it is important to know exactly what kind of machine we are working with.

The 3D printer used in this project is the model BCN3D+ by CIM Foundation (BCN3D technologies) which is and OpenSource based machine. This means that the community takes an active role in its development and is constantly improving the firmware and the software. The other elements which are always being upgraded are the parts of the machine. This printer is partly constructed using 3D printed parts. This parts can be printed by the own printer which makes it an auto replicant technology, which makes it really interesting, especially in an academic and learning point of view.

12.1. Basic specifications

The basic aspects of the printer are shown in the following table (table A2.1.):

Print Technology	Extrusion Fused Filament Fabrication (FFF)
Physical Dimensions	480mm x 480mm x 455mm
Weight	13kg (without spool)
Printing Volume	Length: 252mm Width: 200mm Height:200mm
Number of extruders	1 (upgradable to 2)
Layer Height	0,1-0,35mm (with standard 0,4 mm nozzle) 0,2-0,5mm (with 0,6mm nozzle)
Positioning resolution	X axis: 0,05mm Y axis: 0,05mm Z axis: 0,1mm
Working temperature Max. Hot bed temperature Max. extruder temperature	15-35°C 80°C (measured on the perimeter) 260°C
Filament diameter	3mm / 1,75mm
Compatible materials	PLA ABS Nylon HIPS PVA Laybrick (with 0,6mm nozzle)

	Laywood (with 0,6mm nozzle) Filaflex (with 0,6mm nozzle)
Electronics	Arduino Mega 2560+RAMPS 1.4
Connectivity	SD Card (autonomous operation) USB Cable (controlled through Repetier Host)
Firmware	BCN3D+ specific (based on Marlin)
Compatible files	.STL
Code converter software	Slic3r, Cura
AC Input	AC 100-240V, 4 amps, 50-60Hz
Power requirements	200W

Table A4.1: BCN3D+'s basic specifications from https://www.bcn3dtechnologies.com

It is also important to mention the technology used to gather, melt and then deposit the material. A pressing wheel drags down the filament to the hot end, which heats it and makes the melted material go through the nozzle, which deposits the material in the hot bed. After the layer has been drawn, the machine moves the extruder set the necessary vertical distance and the process is repeated all over again (Figure A4.1.).

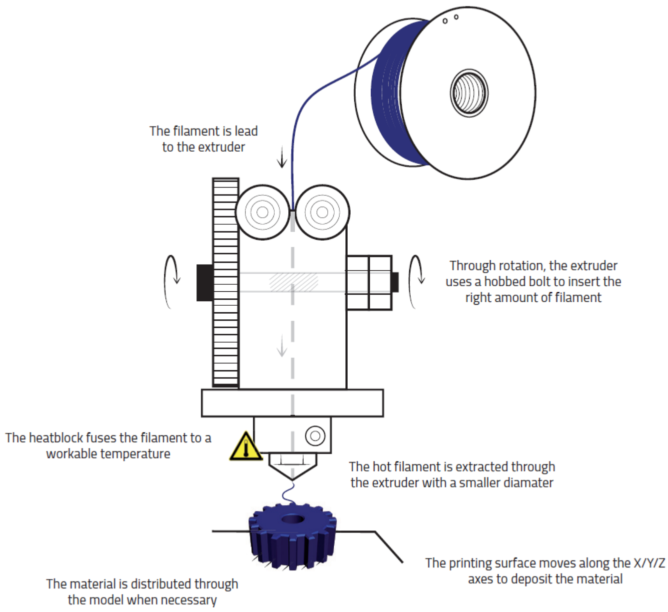
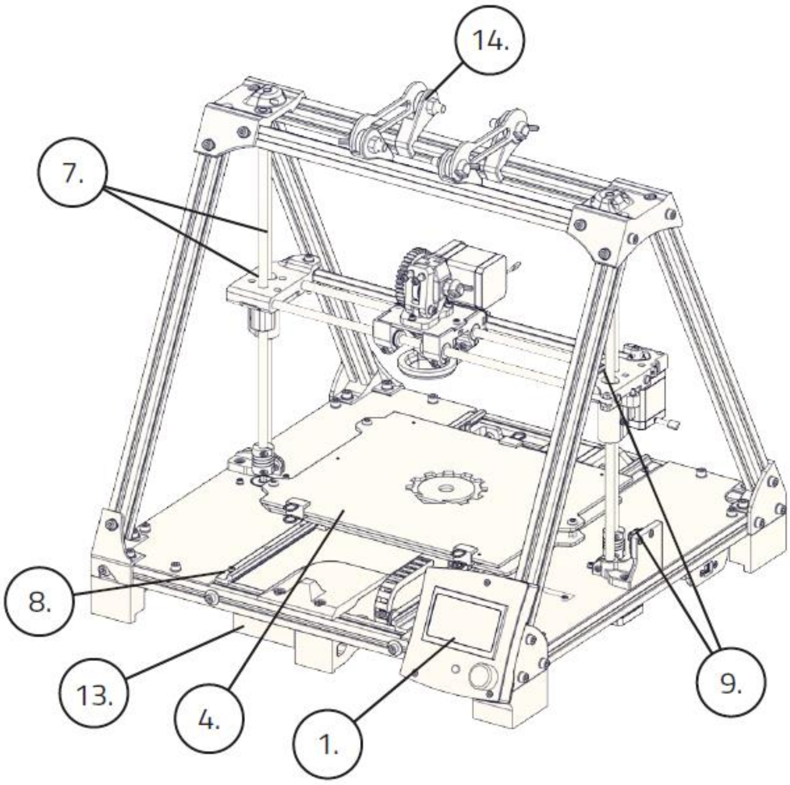


Figure A4.1: Material flow over the printing process from https://www.bcn3dtechnologies.com

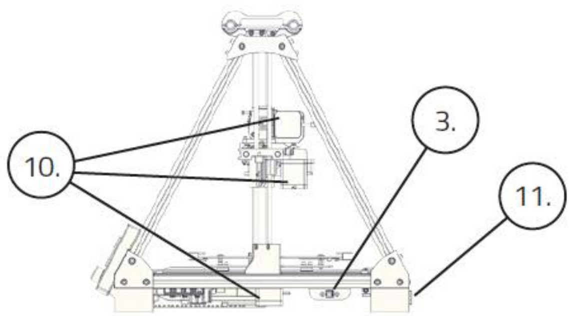
12.2. BCN3D+ parts

Perspective

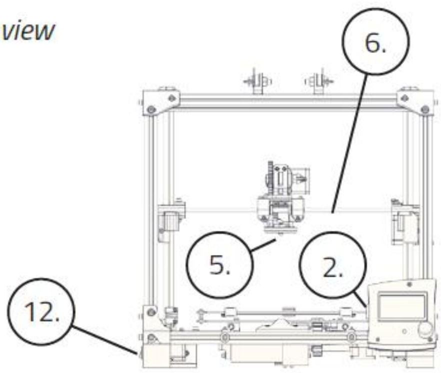


1. LCD Screen
2. SD Card Slot
3. USB Connector
4. Hotbed
5. Hotend (Extruder)
6. X axis guides
7. Threaded rod and Z axis guides
8. Y axis linear guides
9. Mechanical endstops
10. Stepper motors
11. Outlet
12. ON/OFF button
13. Power supply
14. Spool holder

Left view



Front view



Extruder (Hotend)

1. Heatsink
2. Heat break
3. Heatblock
4. Nozzle

Head

5. Idler
6. Tightening screws
7. Layer fan
8. Hotend fan
9. X axis carriage

Electronics

10. Pololus
11. Arduino + RAMPS

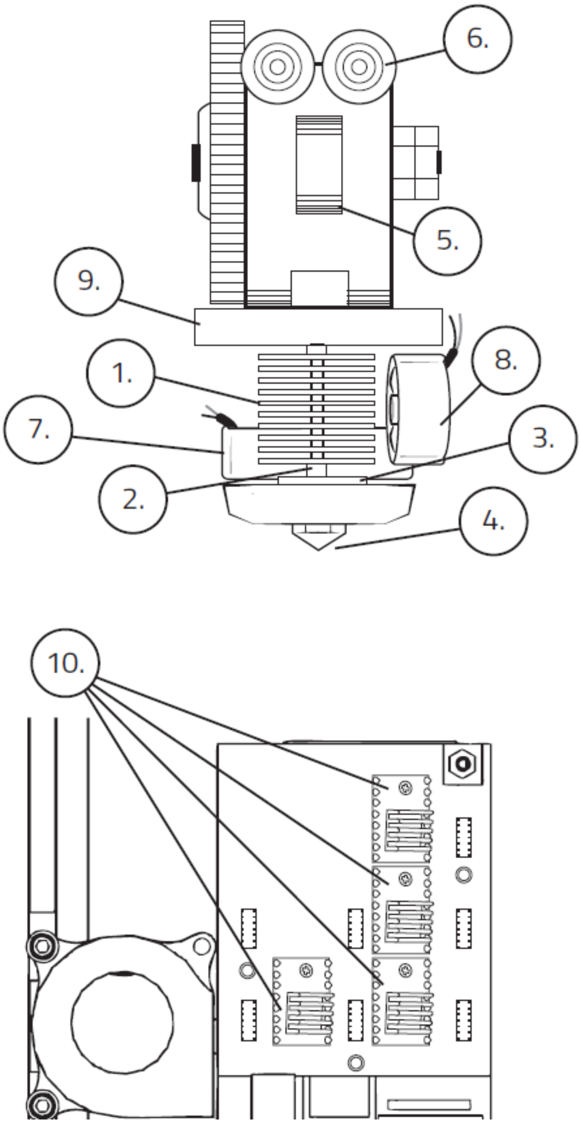


Figure A4.2: BCN3D+'s parts from https://www.bcn3dtechnologies.com

12.3. Set up process

Hotbed height calibration

For a proper use, the nozzle movement must be parallel to the Hotbed Surface (Figure A4.2).
To achieve that, there are three screws available to calibrate its orientation.

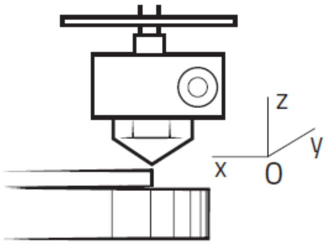


Figure A4.3: Hotbed height calibration from https://www.bcn3dtechnologies.com

There's a risk of the nozzle hitting the hotbed glass or the first layer not sticking on its surface when decalibrated. The following steps must be followed.

1. Click autohome (Prepare/Autohome) so the printer axes move to their initial position. The first time, caution should be exercised because the nozzle can collide with the base plate. If it is anticipated that this will happen, manually press the Z axis end stopper.

2. Adjust the screw triggering the endstop so the nozzle almost touches the glass when clicking Auto-home (Figure A2.4.).

3. Tighten or loosen the three black screws levelling the base plate. The distance between the nozzle and the glass should be 0,2mm. (Tip: use a folded paper to check) (Figure A2.4.).

4. Position the extruder in the left side using your hand (in case any resistance is felt, disable the stepper motors using prepare>Disable Stepper). Level that base plate once again using the same procedure.

5. Move the base plate to the front to level the rear end of the plate.

6. Repeat the process until its four corners are levelled.

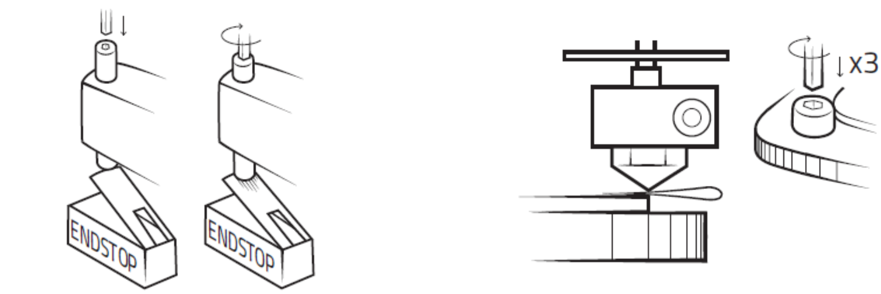


Figure A4.4: Steps 2 and 3 of Hotbed height calibration from https://www.bcn3dtechnologies.com

Loading the filament

One of the more common operations in a 3D printer is the loading and unloading of filament: change of colour, change of material, using a new spool, cleaning, maintenance…

In order to do so, the following steps must be followed:

1. Heat the extruder. Warm the hotend up to printing temperature.
2. Click on Prepare>Move axis>1mm>Extruder, and rotate the wheel slightly clockwise (positive values) to extrude a few millimetres of material. This procedure will help prevent jams.
3. Click on Prepare>Move axis>1mm>Extruder, and rotate the wheel anticlockwise (negative values) moving the gear steps back until the filament is free.
4. Once the old thread is out, load the new one. Click on Prepare>Move axis>1mm>Extruder so the screws hold it tight. Move the wire slowly until the material exits through the end of the hotend.
5. For proper filament feeding, the idler screws must be tightened enough, offering a slight resistance when assisted with our fingers.
6. Once the extruder starts pulling the filament, tighten the screws until enough pressure is reached.
7. Once these steps are followed, the filament will be loaded and ready to print.

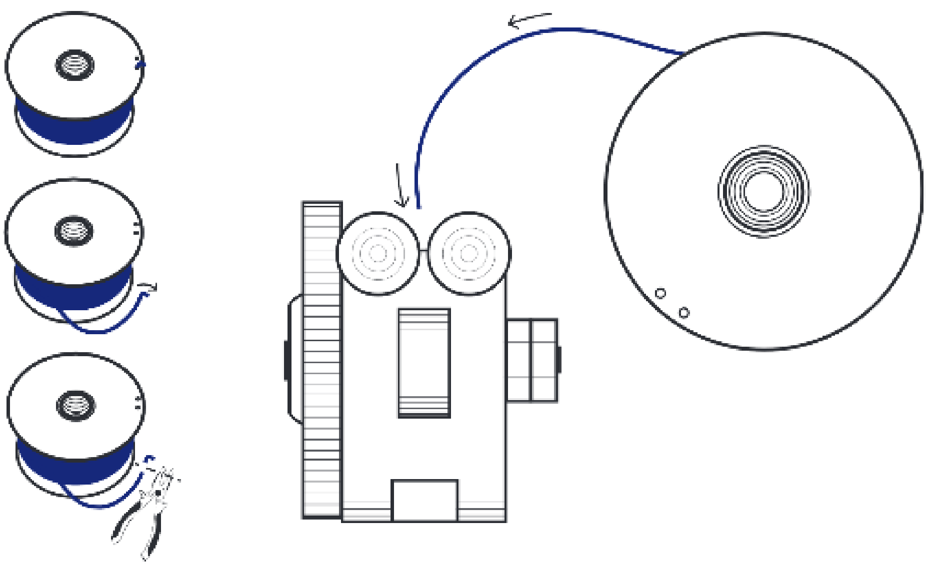


Figure A4.5: Loading process from https://www.bcn3dtechnologies.com

12.4. LCD control

The BCN3D+ can be operated from its LCD menu, a single button combining two movements (Figure A4.6):

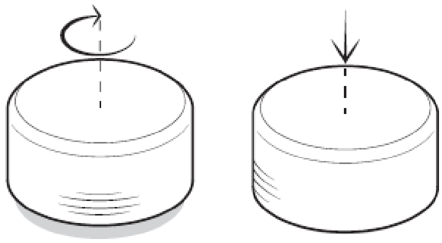


Figure A4.6: Control buttons movements from https://www.bcn3dtechnologies.com

1. Turn to move through the menu.
2. Click to select desired option.

Adjacently to the control button there is an emergency red button to stop the machine in case of malfunction. It stops the printer but keeps the screen and fans on. Once pressed, the printer resets itself to resume use.

Just for reference, the full menu diagram of LCD Control shows below:

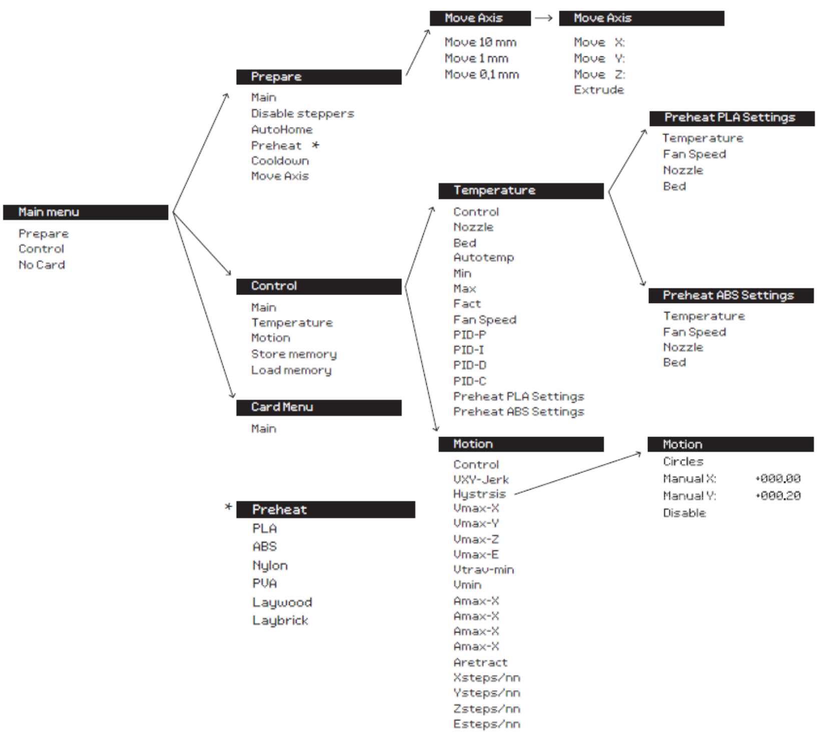


Figure A4.7: Full menu's diagram from https://www.bcn3dtechnologies.com

12.5. Print from SD /No SD

To transfer the G-Code to the printer to start the print, there are available two different procedures.

1. Using the LCD. Insert an SD containing the G-Code file of the sample in the lateral slot card of the screen and press the control button and choose Print from SD to select the object.

2. PC connection. Use software to connect the printer via USB. For example, Repetier Host is a free open source program that allows you to visualize .STL files, automatically generate the G-Code form preconfigured profiles and monitor the printing process.

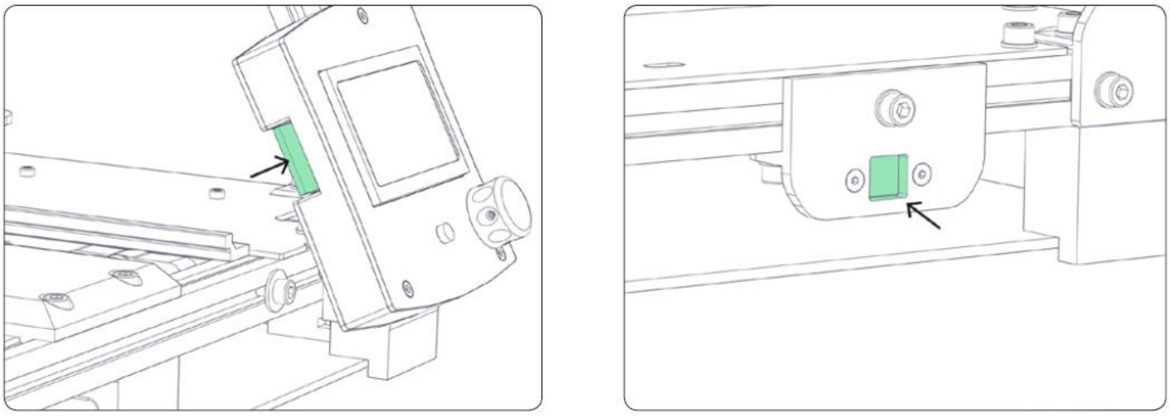


Figure A4.8: On the left, printo from SD; on the right, connect via USB cable from https://www.bcn3dtechnologies.com